CHAPTER 5. ENGINEERING ANALYSIS

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CHAPTER 5. ENGINEERING ANALYSIS

5.1 INTRODUCTION

This chapter provides the technical support documentation on the engineering analysis, evaluating both liquid-immersed and dry-type distribution transformers. The purpose of the engineering analysis is to estimate the relationship between the manufacturer's selling price of a transformer and its corresponding efficiency rating. This relationship serves as the basis for the subsequent cost-benefit calculations for individual customers, manufacturers, and the nation (see Chapter 8, Life-Cycle Cost and Payback Period Analyses).

5.2 STRUCTURING THE ENGINEERING ANALYSIS

As discussed in the market and technology assessment (Chapter 3), distribution transformers are classified by their insulation type (liquid-immersed or dry-type), the number of phases (single or three), the primary voltage (low-voltage or medium-voltage for dry-types) and the basic impulse insulation level (BIL) rating (for dry-types). Following this convention, the U.S. Department of Energy (DOE) developed ten equipment classes, shown in Table 5.2.1. These equipment classes were adapted from the National Electrical Manufacturers Association (NEMA)'s TP 1 classification system, although they do not follow the classification system precisely. NEMA's TP 1 classifies medium-voltage, dry-type distribution transformers into two equipment classes, ≤ 60 kilovolt (kV) BIL and > 60 kV BIL. Based on input from manufacturers, DOE elected to increase the differentiation of medium-voltage, dry-type transformers, and create three equipment classes of BIL ratings: 20–45 kV BIL, 46–95 kV BIL, and ≥ 96kV BIL (see Chapter 3, section 3.3).

Within each of these equipment classes, DOE further classified distribution transformers by their kilovolt-ampere (kVA) rating. These kVA ratings are essentially size categories, indicating the power handling capacity of the transformers. Due to differences in construction methods and material properties, efficiency levels vary by both equipment class and kVA rating. For NEMA's TP 1-2002,[1] there are 99 kVA ratings across all the equipment classes (see Chapter 3, section 3.7.1). For DOE's rulemaking, because of the greater degree of differentiation around the BIL rating in medium-voltage, dry-type transformers, there are 115 kVA ratings across all the equipment classes, as shown in Table 5.2.1.

[1] NEMA's TP 1-2002 can be found online at: http://www.nema.org/stds/tp1.cfm#download.

Table 5.2.1 Equipment Classes and Number of kVA Ratings

Distribution Transformer Equipment Class	kVA Range	Number of kVA Ratings
1. Liquid-immersed, medium-voltage, single-phase	10–833	13
2. Liquid-immersed, medium-voltage, three-phase	15–2500	14
3. Dry-type, low-voltage, single-phase	15–333	9
4. Dry-type, low-voltage, three-phase	15–1000	11
5. Dry-type, medium-voltage, single-phase, 20-45 kV BIL	15–833	12
6. Dry-type, medium-voltage, three-phase, 20-45 kV BIL	15–2500	14
7. Dry-type, medium-voltage, single-phase, 46-95 kV BIL	15–833	12
8. Dry-type, medium-voltage, three-phase, 46-95 kV BIL	15–2500	14
9. Dry-type, medium-voltage, single-phase, ≥ 96 kV BIL	75–833	8
10. Dry-type, medium-voltage, three-phase, ≥ 96 kV BIL	225–2500	8
	Total	115

DOE recognized that it would be impractical to conduct a detailed engineering analysis of the manufacturer's selling price-efficiency relationship on all 115 kVA ratings, so it sought to develop an approach that simplified the analysis while retaining reasonable levels of accuracy. DOE consulted with industry representatives and transformer design engineers and developed an understanding of the construction principles for distribution transformers. It found that many of the units share similar designs and construction methods. Thus, DOE simplified the analysis by creating 13 engineering design lines, which group together kVA ratings based on similar principles of design and construction. The 13 design lines subdivide the equipment classes, to improve the accuracy of the engineering analysis. These 13 engineering design lines differentiate the transformers by insulation type (liquid-immersed or dry-type), number of phases (single or three), and primary insulation levels for medium-voltage, dry-type (three different BIL levels).

DOE then selected one unit from each of the engineering design lines for study in the engineering analysis and the life-cycle cost (LCC) analysis (see Chapter 8), reducing the number of units for analysis from 115 to 13. It then extrapolated the results of its analysis from the unit studied to the other kVA ratings within that same engineering design line. DOE performed this extrapolation in the national impacts analysis (see Chapter 10). The technique it used to extrapolate the findings on the representative unit to the other kVA ratings within a design line is referred to as "the 0.75 scaling rule." This rule states that, for similarly designed transformers, costs of construction and losses scale to the ratio of kVA ratings raised to the 0.75 power. The relationship is valid where the optimum efficiency loading points of the two transformers being scaled are the same. An example of how DOE applied this scaling appears in section 5.2.1 of this chapter. A technical discussion on the derivation of the 0.75 scaling rule appears in Appendix 5B.

Table 5.2.2 presents DOE's 13 design lines and the representative units selected from each engineering design line for analysis. Descriptions of each of the design lines and the rationale behind the selection of the representative units follow Table 5.2.2.

Table 5.2.2 Engineering Design Lines (DLs) and Representative Units for Analysis

EC*	DL	Type of Distribution Transformer	kVA Range	Representative Unit for this Engineering Design Line
1	1	Liquid-immersed, single-phase, rectangular tank	10–167	50 kVA, 65°C, single-phase, 60Hz, 14400V primary, 240/120V secondary, rectangular tank
	2	Liquid-immersed, single-phase, round tank	10–167	25 kVA, 65°C, single-phase, 60Hz, 14400V primary, 120/240V secondary, round tank
	3	Liquid-immersed, single-phase	250–833	500 kVA, 65°C, single-phase, 60Hz, 14400V primary, 277V secondary
2	4	Liquid-immersed, three-phase	15–500	150 kVA, 65°C, three-phase, 60Hz, 12470Y/7200V primary, 208Y/120V secondary
	5	Liquid-immersed, three-phase	750–2500	1500 kVA, 65°C, three-phase, 60Hz, 24940GrdY/14400V primary, 480Y/277V secondary
3	6	Dry-type, low-voltage, single-phase	15–333	25 kVA, 150°C, single-phase, 60Hz, 480V primary, 120/240V secondary, 10kV BIL
4	7	Dry-type, low-voltage, three-phase	15–150	75 kVA, 150°C, three-phase, 60Hz, 480V primary, 208Y/120V secondary, 10kV BIL
	8	Dry-type, low-voltage, three-phase	225–1000	300 kVA, 150°C, three-phase, 60Hz, 480V Delta primary, 208Y/120V secondary, 10kV BIL
6	9	Dry-type, medium-voltage, three-phase, 20-45kV BIL	15–500	300 kVA, 150°C, three-phase, 60Hz, 4160V Delta primary, 480Y/277V secondary, 45kV BIL
	10	Dry-type, medium-voltage, three-phase, 20-45kV BIL	750–2500	1500 kVA, 150°C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL
8	11	Dry-type, medium-voltage, three-phase, 46-95kV BIL	15–500	300 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
	12	Dry-type, medium-voltage, three-phase, 46-95kV BIL	750–2500	1500 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL
10	13	Dry-type, medium-voltage, three-phase, 96-150kV BIL	225–2500	2000 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 125kV BIL

* EC means equipment class (see Chapter 3 of the TSD). DOE did not select any representative units from the single-phase, medium-voltage equipment classes (EC5, EC7 and EC9), but calculated the analytical results for EC5, EC7, and EC9 based on the results for their three-phase counterparts.

DOE divided liquid-immersed transformers into five engineering design lines, based on their tank shape, number of phases, and kVA ratings. DOE believes that this breakdown enables the analysis to identify and capture a more accurate representation of the manufacturer's selling price and efficiency relationship. DOE broke dry-type distribution transformers into eight engineering design lines, primarily according to their BIL levels. DOE believes this level of disaggregation is necessary to capture important differences in the price-efficiency relationship, particularly as the BIL level varies. For example, a 300 kVA, three-phase, dry-type unit could be classified in design lines 8, 9, or 11, or 13, depending on whether the BIL rating is 10 kV (low-voltage), 20-45 kV, 46-95 kV, or 96-150 kV.

For design lines 9 through 13, the representative units selected for some of the dry-type design lines may not be the standard BILs associated with a given primary voltage. DOE selected a slightly higher BIL for the representative units from these design lines to ensure that any minimum efficiency standard would not excessively penalize customers purchasing transformers at higher BIL ratings within the range. For example, a 300 kVA transformer with a 4160V primary is called a "5kV class" transformer and would normally be built with a 30kV

BIL. However, customers may also choose to order this transformer with 45kV BIL or 60kV BIL. If the candidate minimum efficiency standard were set based on a 30kV BIL, it may not be possible to achieve that same efficiency rating for customers ordering 60kV BIL. Thus, DOE evaluated the middle BIL level (in this example, 45kV BIL), making it slightly easier to comply for a lower BIL, and not too difficult (or impossible) for the higher BIL.

The remainder of this section discusses each of the 13 engineering design lines, providing a description and explanation of the transformers covered.

Design Line 1. This is the basic, high-volume line for rectangular-tank, single-phase, liquid-immersed distribution transformers, ranging from 10 kVA to 167 kVA. Transformers in this design line typically have BILs ranging from 30 kV to 150 kV and a tap configuration of four 2½ percent taps—two above and two below the nominal voltage. Tap configurations enable transformer users to maintain full (rated) output voltage by slightly increasing or decreasing the number of turns in the primary in anticipation of an input voltage slightly above or below the rated nominal. This design line has a primary voltage less than 35 kV, and a secondary voltage less than or equal to 600 Volts (V).

The representative unit selected for design line 1 is a 50 kVA pad-mounted unit, as this is a high shipment volume rating, and is approximately the middle of the kVA range for this design line (10 kVA, 15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA, 100 kVA, and 167 kVA). Engineering design considerations and manufacturing differences led to the placement of 250 kVA and higher-rated units in design line 3.

Design Line 2. This is the basic, high-volume line for round-tank (pole-mounted), single-phase, liquid-immersed distribution transformers, ranging from 10 kVA to 167 kVA. Although some manufacturers tend to employ the same basic core/coil design for design line 1 and design line 2, others may have design differences between pad-mounted and pole-mounted transformers. DOE decided to analyze these two types of distribution transformers separately for the engineering and LCC analyses. Transformers in design line 2 typically have BILs ranging from 30 kV to 150 kV, a tap configuration of four 2½ percent taps—two above and two below the nominal, a primary voltage less than 35 kV, and a secondary voltage less than or equal to 600 V.

The representative unit selected for design line 2 is a 25 kVA pole-mounted unit, as this is a high-volume rating for pole-mounted transformers, and is on the lower end of the kVA range for this design line (10 kVA, 15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA, 100 kVA, and 167 kVA).   Engineering design considerations and manufacturing differences led to the placement of 250 kVA and higher-rated units in design line 3.

Design Line 3. This design line groups together single-phase, round-tank, liquid-immersed distribution transformers, ranging from 250 kVA to 833 kVA. Together, design lines 1 through 3 cover all the single-phase, liquid-immersed units (there are no standard kVA ratings between 167 and 250 kVA). Transformers in this design line typically have BILs ranging from 30 kV to 150 kV, a tap configuration of four 2½ percent taps—two above and two below the nominal, a primary voltage less than 35 kV, and a secondary voltage less than or equal to 600 V.

The representative unit selected for design line 3 is a 500 kVA round-tank, as this rating occurs in the middle of the kVA range for this design line (250 kVA, 333 kVA, 500 kVA, 667 kVA, and 833 kVA). Although high currents result from having a 277 V secondary at the larger kVA ratings, high current bushings are available, and a market does exist for these transformers.

Design Line 4. Design line 4 represents rectangular tank, three-phase, liquid-immersed distribution transformers, ranging from 15 kVA to 500 kVA. Transformers in this design line typically have BILs ranging from 30 kV to 150 kV, a tap configuration of four 2½ percent taps—two above and two below the nominal, a primary voltage less than 35 kV, and a secondary voltage less than or equal to 600 V.

The representative unit selected for design line 4 is a 150 kVA transformer, as this is a common rating in this design line and occurs approximately in the middle of the kVA range (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 300 kVA, and 500 kVA).

Design Line 5. Design line 5 represents rectangular tank, three-phase, liquid-immersed distribution transformers, ranging from 750 kVA to 2500 kVA. Together, design lines 4 and 5 cover all the three-phase, liquid-immersed units (there are no standard kVA ratings between 500 and 750 kVA). Transformers in this design line typically have BILs ranging from 95 kV to 150 kV, a tap configuration of four 2½ percent taps—two above and two below the nominal, a primary voltage less than 35 kV, and a secondary voltage less than or equal to 600 V.

The representative unit selected for this design line is a 1500 kVA transformer, as this is a common rating in this size range, and occurs in the middle of the kVA range for this design line (750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

Design Line 6. Design line 6 represents single-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 333 kVA. Transformers in this design line typically have BIL ratings of 10 kV and a "universal" tap arrangement, meaning six 2½ percent taps, two above and four below the nominal. DOE selected this tap arrangement based on recommendations from manufacturers who produce transformers at these ratings. The primary and secondary voltages are both 600 V or below.

The representative unit selected for design line 6 is a 25 kVA transformer, as this is a common rating in this size range, and occurs toward the low end of the kVA ratings for this design line (15 kVA, 25 kVA, 37.5 kVA, 50 kVA, 75 kVA, 100 kVA, 167 kVA, 250 kVA, and 333 kVA).

Design Line 7. Design line 7 represents three-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 150 kVA. Because the kVA range of three-phase ratings is broad and construction techniques differ, DOE split the range of three-phase, low-voltage, dry-type transformers into design line 7 and design line 8, so the engineering differences in core-coil design and manufacturing would be more readily apparent. Transformers in this design line typically have BIL ratings of 10 kV and a "universal" tap arrangement, meaning six 2½ percent taps, two above and four below the nominal. The primary and secondary voltages are both 600 V or below.

The representative unit selected for design line 7 is a 75 kVA transformer, as this is a common rating in this size range, and occurs in the middle of the kVA ratings for this design line (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, and 150 kVA).

Design Line 8. Design line 8 represents three-phase, low-voltage, ventilated dry-type distribution transformers, ranging from 225 kVA to 1000 kVA. Transformers in this design line typically have BIL ratings of 10 kV and a "universal" tap arrangement, meaning six 2½ percent taps, two above and four below the nominal. The primary and secondary voltages are both 600 V or below.

The representative unit selected for design line 8 is a 300 kVA transformer, as this is a common rating in this size range, and occurs toward the lower end of the range of kVA ratings included in this design line (225 kVA, 300 kVA, 500 kVA, 750 kVA, and 1000 kVA).

Design Line 9. Design line 9 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 500 kVA. To accommodate the broad kVA range and to allow for engineering differences in construction principles and associated costs, DOE split the three-phase, medium-voltage, dry-type units into design lines 9 and 10. Transformers in design line 9 typically have primary voltages less than or equal to 5 kV with a BIL rating between 20 kV and 45 kV. The secondary voltage is less than or equal to 600 V and the tap arrangement is typically four 2½ percent taps, two above and two below the nominal.

The representative unit selected for design line 9 is 300 kVA, as this is a common rating in this size range, and occurs near the high end of the kVA ratings for this design line (15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 300 kVA, and 500 kVA).

Design Line 10. Design line 10 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 750 kVA to 2500 kVA. Transformers in this design line typically have primary voltages less than or equal to 5 kV with a BIL rating between 20 kV and 45 kV. The secondary voltage is less than or equal to 600 V and the tap arrangement is typically four 2½ percent taps, two above and two below the nominal.

The representative unit selected for this design line is a 1500 kVA transformer, as this is a common rating, and occurs in the middle of the kVA range for this design line (750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

Design Line 11. Design line 11 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 15 kVA to 500 kVA. This design line parallels design line 9, with a higher primary insulation level, 46 kV to 95 kV BIL. Because dry-type transformer designs and, more importantly, the efficiency of those designs, are strongly influenced by changes in BIL, DOE considered these higher BIL ratings separately. The typical tap arrangement is four 2½ percent taps, two above and two below the nominal. The primary voltage is typically less than or equal to 15 kV and the secondary voltage is less than or equal to 600 V.

The kVA ratings in design line 11 are 15 kVA, 30 kVA, 45 kVA, 75 kVA, 112.5 kVA, 150 kVA, 225 kVA, 300 kVA, and 500 kVA. The shipments for this design line are primarily in the kVA range inclusive of and between 225 kVA and 500 kVA; therefore, DOE selected the 300 kVA rating as the representative unit for analysis.

Design Line 12. Design line 12 represents three-phase, medium-voltage, ventilated dry-type distribution transformers, ranging from 750 kVA to 2500 kVA. This design line parallels design line 10, with a higher primary insulation level, 46 kV to 95 kV BIL. The typical tap arrangement is four 2½ percent taps, two above and two below the nominal. The primary voltage is typically less than or equal to 15 kV and the secondary voltage is less than or equal to 600 V.

The representative unit selected for this design line is a 1500 kVA transformer, as it is a common rating in this size range and BIL rating, and it occurs in the middle of the kVA range covered by this design line (750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

Design Line 13. As a further extension on the dry-type, three-phase, medium-voltage BIL ranges, DOE analyzed 96 kV to 150 kV BIL, in a design line ranging from 225 kVA to 2500 kVA. The 225 kVA rating is considered to be the lowest kVA rating where one would expect to see a unit with a BIL greater than 110 kV. The typical tap arrangement is four 2½ percent taps, two above and two below the nominal. The primary voltage is typically less than or equal to 35 kV and the secondary voltage is less than or equal to 600 V.

This third set of dry-type, three-phase, medium-voltage distribution transformers spans a smaller range of kVA ratings, 225 kVA to 2500 kVA. As most of the sales activity in this design line occurs in the higher kVA ratings, the representative unit selected for design line 13 is a 2000 kVA transformer. This unit is a common rating in this size range, and occurs toward the high end of the range covered by this design line (225 kVA, 300 kVA, 500 kVA, 750 kVA, 1000 kVA, 1500 kVA, 2000 kVA, and 2500 kVA).

In addition to the three equipment classes for dry-type, medium-voltage, three-phase distribution transformers (for which there are five engineering design lines) presented in Table 5.2.1, there are three equipment classes for single-phase, dry-type, medium-voltage units. As discussed in Chapter 3, the shipment volume for single-phase, dry-type, medium-voltage transformers is very low as a percentage of the total dry-type shipments. Additionally, the total megavolt-ampere (MVA) capacity of single-phase, dry-type, medium voltage transformers is relatively low as a percentage of the total MVA capacity for dry-type, medium voltage transformers. Therefore, it does not warrant the level of effort involved in conducting analysis on these specific units. DOE decided instead to scale the analysis findings from three-phase units to the single-phase units by establishing the same energy conservation standard requirement on a 'per phase' basis. In other words, DOE would scale the energy conservation standard requirements for a three-phase 1500 kVA medium-voltage dry-type to be the same for a single-phase 500 kVA medium-voltage dry-type unit. In this way, DOE was able to concentrate resources and improve the accuracy in other, higher volume and more important distribution transformer equipment classes. DOE used the same approach in the previous rulemaking for distribution transformers.

5.2.1 Summary of Design Line Coverage

The following four tables summarize the coverage of each of the design lines in relation to the various equipment classes and kVA ratings. The abbreviation DL stands for design line, and the row in the table where the phrase "Rep Unit" appears indicates the kVA rating of the representative unit from that design line. The representative unit is the kVA rating that DOE analyzed in the engineering and LCC analyses. For example, DL1 stands for design line 1, spanning from 10 to 167 kVA liquid-type, single-phase. The label "Rep Unit" appears in row 50 kVA, indicating that the 50 kVA is the representative unit for DL1. Similarly, the representative unit for DL2 is the 25 kVA unit.

There are five liquid-immersed transformer design lines, three single-phase and two three-phase, as shown in Table 5.2.3. To capture any design differences between a single-phase pole and a pad-mounted transformer, DOE analyzed units in both DL1 and DL2, spanning the same kVA ratings (10 kVA to 167 kVA). On the three-phase liquid-immersed side, there is no overlap between those two design lines.

Table 5.2.3 Liquid-Immersed Design Lines and Representative Units

Equipment Class 1 Liquid-Immersed, Single-Phase		
kVA	Rectangular Tank	Round Tank
10	DL 1	DL 2
15	DL 1	DL 2
25	DL 1	DL 2 Rep Unit
37.5	DL 1	DL 2
50	DL 1 Rep Unit	DL 2
75	DL 1	DL 2
100	DL 1	DL 2
167	DL 1	DL 2
250	DL 3	DL 3
333	DL 3	DL 3
500	DL 3	DL 3 Rep Unit
667	DL 3	DL 3
833	DL 3	DL 3

Equipment Class 2 Liquid-Immersed, Three-Phase	
kVA	Design Lines
15	DL 4
30	DL 4
45	DL 4
75	DL 4
112.5	DL 4
150	DL 4 Rep Unit
225	DL 4
300	DL 4
500	DL 4
750	DL 5
1000	DL 5
1500	DL 5 Rep Unit
2000	DL 5
2500	DL 5

Table 5.2.4 presents the low-voltage, dry-type design lines. For single-phase units, one design line spans all nine kVA ratings. For the three-phase units, two design lines cover the 11 kVA ratings in that equipment class. There is no overlap in the design lines for low-voltage dry-type transformers.

Table 5.2.4 Dry-Type, Low-Voltage Design Lines and Representative Units

Equipment Class 3 Dry-Type, Low Voltage, Single-Phase	
kVA	**Design Line**
15	
25	Rep Unit
37.5	
50	
75	DL 6
100	
167	
250	
333	

Equipment Class 4 Dry-Type, Low Voltage, Three-Phase	
kVA	**Design Line**
15	
30	
45	DL 7
75	Rep Unit
112.5	
150	
225	
300	Rep Unit
500	DL 8
750	
1000	

Table 5.2.5 presents equipment classes (abbreviated "EC" in this table) for medium-voltage, single-phase, dry-type units. As discussed in Chapter 3, section 3.4 (National Shipment Estimate), these units have a low shipment volume and low total MVA capacity. All three equipment classes shown in Table 5.2.5 together represent less than one-quarter of one percent of dry-type shipments on an MVA capacity basis, and less than one percent of medium-voltage dry-type shipments on an MVA capacity basis. Thus, DOE did not consider it appropriate to conduct analysis of any units from these three equipment classes.

As an alternative to investing time and resources analyzing these low-volume units, DOE used the results from the medium-voltage, three-phase, dry-type units (presented in Table 5.2.6) and divided those findings by three, creating virtual (calculated) representative units (labeled as "Virtual RU" in Table 5.2.5) for these three equipment classes. DOE used the representative units from design lines 9, 10, 11, 12, and 13. These virtual representative units are shown in their respective rows, following the application of the quotient. For example, in the single phase (20-45kV BIL) column, the representative unit from DL9 is a three-phase 300 kVA unit (see Table 5.2.6), so it scales to a single-phase, 100 kVA unit in Table 5.2.5.

Table 5.2.5 Dry-Type, Medium-Voltage, Single-Phase Design Lines

Dry-Type, Medium Voltage, Single-Phase			
kVA	EC 5 Low BIL 20-45kV	EC 7 Med BIL 46-95kV	EC 9 High BIL ≥96kV
15			-
25			-
37.5			-
50	DL9 / 3	DL11 / 3	-
75			
100	Virtual RU	Virtual RU	
167			
250			DL13 / 3
333	DL10 / 3	DL12 / 3	
500	Virtual RU	Virtual RU	
667			Virtual RU
833			

Table 5.2.6 presents the equipment classes (abbreviated "EC" in this table) for the medium-voltage, three-phase, dry-type distribution transformers and each of the design lines and respective representative units. For those equipment classes with a higher volume and larger range of kVA ratings, DOE used two separate design lines for each, to maintain accuracy. However, for the very high BIL levels (≥ 96kV BIL), one design line (DL13) covers all the ratings from 225kVA to 2500kVA. Within DL13, DOE did not extrapolate the results of this unit to ratings of 150kVA and below because there were no shipments at these ratings in the shipments analysis and it is very unlikely that they would be built.

Table 5.2.6 Dry-Type, Medium-Voltage, Three-Phase Design Lines

Dry-Type, Medium Voltage, Three-Phase			
kVA	EC 6 Low BIL 20-45kV	EC 8 Med BIL 46-95kV	EC 10 High BIL ≥96kV
15			-
30			-
45			-
75			-
112.5	DL 9	DL 11	-
150			-
225			
300	Rep Unit	Rep Unit	
500			
750			
1000			DL 13
1500	Rep Unit DL 10	Rep Unit DL 12	
2000			Rep Unit
2500			

5.2.2 Scaling Relationships in Transformer Manufacturing

DOE simplified the engineering analysis by creating design lines, selecting representative units from these design lines, and scaling the results of the analysis on these representative units within their respective design lines. This section briefly introduces the scaling relationship DOE used to extrapolate the findings on the representative units to the other kVA ratings. A more detailed discussion of the derivation of the 0.75 scaling rule is provided in Appendix 5B.

The scaling formulae are mathematical relationships that exist between the kVA ratings and the physical size, cost, and performance of transformers. The size-versus-performance relationships arise from fundamental equations describing a transformer's voltage and kVA rating. For example, when the kVA rating, voltage, and frequency are fixed, the product of the conductor current density, core flux density, core cross-sectional area, and total conductor cross-sectional area is constant.

To illustrate this point, consider a transformer with four fixed variables: frequency, magnetic flux density, current density, and BIL rating. If one enlarges (or decreases) the kVA rating, then the only parameters free to vary are the core cross-section and the core window area through which the windings pass. Thus, to increase (or decrease) the kVA rating, the dimensions for height, width, and depth of the core/coil assembly scale equally in all directions. Analysis of this scaling relationship reveals that each of the linear dimensions varies as the ratio of kVA ratings to the ¼ power. Similarly, areas vary as the ratios of kVA ratings to the ½ power and volumes vary as the ratio of the kVA ratings to the ¾ or 0.75 power, hence the term "0.75 scaling rule." Application of the 0.75 scaling rule assumes that the efficiency profile of a given transformer will have the same shape as the transformer being scaled. Table 5.2.7 depicts the most common scaling relationships in transformers.

Table 5.2.7 Common Scaling Relationships in Transformers

Parameter Being Scaled	Relationship to kVA Rating (varies with ratio of kVA^x)
Weight	$(kVA_1/kVA_0)^{3/4}$
Cost	$(kVA_1/kVA_0)^{3/4}$
Length	$(kVA_1/kVA_0)^{1/4}$
Width	$(kVA_1/kVA_0)^{1/4}$
Height	$(kVA_1/kVA_0)^{1/4}$
Total Losses	$(kVA_1/kVA_0)^{3/4}$
No-load Losses	$(kVA_1/kVA_0)^{3/4}$

The following three relationships are true as the kVA rating increases or decreases, if the type of transformer (liquid-immersed or dry-type, single-phase or three-phase), the primary voltage, the core configuration, the core material, the core flux density, and the current density (amperes per square inch of conductor cross-section) in both the primary and secondary windings are all held constant:

1. The physical proportions are constant (same relative shape),
2. The eddy loss proportion is essentially constant, and
3. The insulation space factor (voltage or BIL) is constant.

In practical applications, it is rare to find that all of the above are constant over even limited ranges; however, over a range of one order of magnitude in both directions (e.g., from 50 kVA to 5 kVA or from 50 kVA to 500 kVA), the scaling rules shown in Table 5.2.7 can be used to establish reasonable estimates of performance, dimensions, costs, and losses. In practice, these rules can be applied over even wider ranges to estimate general performance levels. DOE's application of the 0.75 scaling rule in this analysis is always less than an order of magnitude.

To illustrate how DOE used the scaling laws, consider two transformers with kVA ratings of S_0 and S_1. The no-load losses (NL) and total losses (TL) of these two transformers would be depicted as NL_0 and TL_0, and NL_1 and TL_1. Then the relationships between the NL and TL of the two transformers could be shown as follows:

Equation 5.2.1

$$NL_1 = NL_0 \times (S_1 / S_0)^{0.75}$$

where:

NL_1 = no-load losses of transformer "1,"

NL_0	=	no-load losses of transformer "0,"
S_1	=	kVA rating of transformer "1," and
S_0	=	kVA rating of transformer "0."

and

Equation 5.2.2

$$TL_1 = TL_0 \times (S_1 / S_0)^{0.75}$$

where:

TL_1	=	total losses of transformer "1," and
TL_0	=	total losses of transformer "0."

Equation 5.2.1 and Equation 5.2.2 can be manipulated algebraically to show that the load loss also varies to the 0.75 power. Starting with the concept that total losses equal no-load losses plus load losses, DOE can derive the relationship for load loss (LL), and show that it also scales to the 0.75 power. Specifically:

Equation 5.2.3

$$LL_1 = TL_1 - NL_1$$

where:

LL_1	=	load losses of transformer "1"

Inserting the TL_1 and NL_1 terms into this equation, DOE finds:

Equation 5.2.4

$$LL_1 = (TL_0 \times (S_1 / S_0)^{0.75}) - (NL_0 \times (S_1 / S_0)^{0.75})$$

Equation 5.2.5

$$LL_1 = (TL_0 - NL_0) \times (S_1 / S_0)^{0.75}$$

Equation 5.2.6

$$LL_1 = (LL_0) \times (S_1 / S_0)^{0.75}$$

where:

LL_0	=	load losses of transformer "0."

Thus, the 0.75 scaling rule can be applied to estimate the losses of a transformer, given the losses and kVA rating of a reference (analyzed) unit. However, in order for this rule to be applicable, the transformer type must be the same, and key parameters—such as the type of core material, core flux density, and conductor current density in the high and low voltage windings—must be fixed. Additionally, use of the 0.75 scaling rule assumes that the efficiency profile of a given transformer will have the same shape as the transformer being scaled. See Appendix 5B for detailed discussion on the derivation of the 0.75 scaling rule.

DOE used the 0.75 scaling rule to scale the analysis findings on each of the representative units within the 13 design lines to the 102 kVA ratings that it did not analyze. DOE applied the scaling rule within the design lines in the national impact analysis (Chapter 10), where it calculated efficiency ratings for the 102 kVA ratings not analyzed.

5.3 TECHNICAL DESIGN INPUTS

For all 13 representative units, the engineering analysis explored the relationship between the manufacturer selling prices and corresponding transformer efficiencies. For this analysis, DOE contracted Optimized Program Service, Inc. (OPS) in Ohio, a software company specializing in transformer design since 1969. Using a range of input parameters and material prices, the OPS software produces a design. This design has specific information about the core and coil, including physical characteristics, dimensions, material requirements, and mechanical clearances, as well as a complete electrical analysis of the final design. This optimized, practical transformer design, the bill of materials, and an electrical analysis report contain sufficient information for a manufacturer to build the unit. DOE uses the software's output to generate an estimated cost of manufacturing materials and labor, which it then converts to a manufacturer selling price by applying markups.

The electrical analysis report estimates the performance of the transformer design (including efficiency) at 25 percent, 35 percent, 50 percent, 65 percent, 75 percent, 100 percent, 125 percent, and 150 percent of nameplate load. The software output provides a clear understanding of the relationship between cost and efficiency because it provides detailed data on design variances, as well as a bill of materials, labor costs, and efficiency. The software does not capture retooling costs associated with changing production designs for a specific manufacturer. In some cases, however, DOE captured tooling costs associated with manufacturing mitered cores by applying adders to the steel price.

5.3.1 A and B Loss Valuation Inputs

One of the inputs to the design software consisted of a range of what are known in the industry as A and B evaluation combinations (see Chapter 3, section 3.6, Total Ownership Cost Evaluation). The combination of A and B input to the design software mimics a distribution transformer purchase order. The A parameter represents a customer's present value of future losses in the transformer core (no-load losses). The B value represents a customer's present value of future losses in the windings (load losses). The B parameter is never larger than A, as this would imply a specification for a transformer whose average load would be more than 100 percent of the nameplate load. The A and B values take into account a range of factors that usually vary from customer to customer.

The A and B values are expressed in terms of dollars per watt of loss. The greater the values of A and B, the greater the importance a customer attaches to the value of future transformer losses. As A and B values increase, the customer places greater importance on reducing the watts of core and winding losses, respectively, and so the customer chooses a more energy-efficient transformer.

DOE used broad ranging combinations of A and B evaluation formulae (presented in Table 5.3.1 and Table 5.3.2) to create a complete set of efficiency levels for each design option combination analyzed. The efficiency levels spanned from a low-first-cost unit to a maximum technologically feasible ("max-tech") design. For the low-first-cost design, the A and B evaluation values were both $0/watt, indicating that the customer does not attach any financial value to future losses in the core or coil of the transformer. For the maximum technologically feasible design, the A and B evaluation values were very high, pushing the software to design at the highest efficiencies achievable.

DOE created its combinations of A and B evaluation formulae combining two techniques to ensure there were sufficient designs in the database for the analysis. The first technique was to create a 'grid' of A and B combinations. The 'grid' technique involved increasing the value of A by a step value, and then increasing the B value from zero to that value of A, using a different step value. Thus, if A had incremental steps of $0.25 and B had steps of $0.20, the combinations would work as follows: ($0.00, $0.00), ($0.25, $0.00), ($0.25, $0.20), ($0.50, $0.00), ($0.50, $0.20), ($0.50, $0.40), ($0.75, $0.00), and so on. Table 5.3.1 presents the ranges and incremental steps for the A and B combinations used in the three grids.

Table 5.3.1 A and B Grid Combinations Used by Software to Generate Design Database

Grid Number	A values and increments	B values and increments	Resultant # of (A, B) combinations
1	$0 to $2 by 0.25 steps	$0 to $2 by 0.20 steps	47
2	$2.50 to $8 by 0.50 steps	$0 to $8 by 0.40 steps	157
3	$9 to $16 by 1.00 steps	$3 to $8 by 0.50 steps	85

The second technique for generating A and B evaluation formulae in the engineering analysis is called the "fan." DOE understands that the ratio of A to B represents an implicit loading for the transformer. Therefore, DOE created a set of (A, B) values in which the B is calculated from the A. The B term is calculated as the A times the percent load squared. In other words, if A equals $1 and DOE is interested in calculating the appropriate B for a 50 percent root-mean-square (RMS) load, then it would be $1 times (0.50)^2, or $0.25. Thus, the combination of ($1.00, $0.25) represents approximately a 50 percent RMS load. As with the "grid," the A values increased with a step function, and B values were calculated as fractions of A so that the ratio of A to B encompassed the RMS loading points that were identified in DOE's loading analysis (i.e., 35 percent and 50 percent). DOE calculated the B values for each A at the following RMS loading points: 5 percent, 10 percent, 15 percent, 20 percent, 25 percent, 30 percent, 35 percent, 40 percent, 45 percent, 50 percent, 55 percent, and 60 percent. Table 5.3.2 presents the range of the two fan combinations used in the analysis.

Table 5.3.2 A and B Fan Combinations Used by Software to Generate Design Database

Fan Number	A values and increments	B values and increments	Resultant # of (A,B) combinations
1	$0 to $2 by 0.50 steps	5% to 60% implicit loading by 5% steps	47
2	$3 to $16 by 1.00 steps	5% to 60% implicit loading by 5% steps	182

When used together, these two techniques created a broad spectrum of A and B combinations as inputs to the OPS software. Figure 5.3.1 illustrates the coverage of designs for the 518 A and B combinations. DOE used each of these A and B pairs with each combination of core steel and winding material analyzed for each representative transformer design line studied.

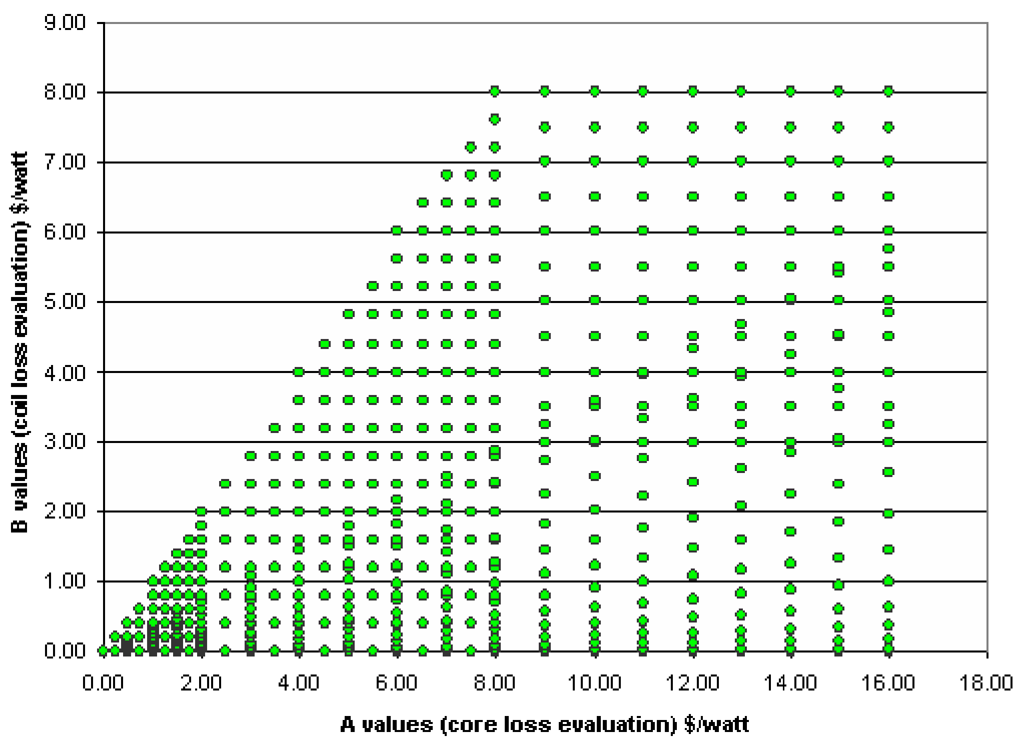

Figure 5.3.1 A and B Combination Software Inputs Used in the Engineering Analysis

Occasionally, the design software generated the same transformer design for two different A and B combinations, creating duplicate designs in the engineering analysis database. DOE removed these duplicate designs before the engineering database was imported into the LCC analysis. Similarly, DOE removed any designs that yielded an efficiency value below the current standard level efficiency.

5.3.2 Core Material Options

DOE understands that there are many ways to build a transformer, even with constant kVA and voltage ratings. For instance, manufacturers can vary the core steels (e.g., M2, M3, M6), the winding materials (aluminum or copper), and core configurations (shell or core-type). For each of the design lines, DOE provides tables listing the design option combinations that it used to analyze each of the representative units. Depending on customer needs, the cost of materials, the capital equipment in their facility, and the skills of their labor force, manufacturers make decisions on how to manufacture a given transformer using different core configurations, core steels, and winding materials. To capture this variation in designs, DOE analyzed the 13 representative units using 5 – 8 different design option combinations of core type, core steel, and winding material. As discussed in the technology assessment (see Chapter 3), core steel is produced in a range of qualities (from an efficiency perspective). M2 core steel is oriented grain silicon steel and has thin laminations, and consequently has very low losses. M12 core steel is non-oriented grain silicon steel and is rolled in thicker laminations, thus contributing to higher core losses. Table 5.3.3 lists all the steel types used in the analysis, and properties associated with these steels. Each steel grade provides the nominal thickness and core losses per pound of steel, under a specified typical magnetic flux density, measured in Tesla (T).

Table 5.3.3 Core Steel Grades, Thicknesses and Associated Losses

Steel Grade	**Nominal Thickness** ***inches***	**Core Loss at 60 Hz** ***Watts per Pound at magnetic flux density****	**Notes / Remarks**
M12	0.014	1.36 Watts/lb at 1.5 T	Non-oriented grain silicon steel
M6	0.014	0.60 Watts/lb at 1.5 T 0.84 Watts/lb at 1.7 T	Grain-oriented silicon steel
M5	0.012	0.51 Watts/lb at 1.5 T 0.74 Watts/lb at 1.7 T	Grain-oriented silicon steel
M4	0.011	0.46 Watts/lb at 1.5 T 0.66 Watts/lb at 1.7 T	Grain-oriented silicon steel
M3	0.009	0.39 Watts/lb at 1.5 T 0.60 Watts/lb at 1.7 T	Grain-oriented silicon steel
M3 Lite Carlite	0.009	0.39 Watts/lb at 1.5 T 0.59 Watts/lb at 1.7 T	Grain-oriented silicon steel with insulative coating
M2	0.007	0.38 Watts/lb at 1.5 T 0.58 Watts/lb at 1.7 T	Grain-oriented silicon steel
M2 Lite Carlite	0.007	0.37 Watts/lb at 1.5 T 0.57 Watts/lb at 1.7 T	Grain-oriented silicon steel with insulative coating
H-0 DR	0.009	0.34 Watts/lb at 1.5 T 0.47 Watts/lb at 1.7 T	Domain-refined, high permeability grade silicon steel
ZDMH	0.009	0.38 Watts/lb at 1.5 T 0.57 Watts/lb at 1.7 T	Imported silicon steel, magnetic domain- refined by mechanical process
SA1	0.001	0.108 Watts/lb at 1.35 T 0.098 Watts/lb at 1.3 T	Amorphous core steel (silicon and boron); flux density limitation - testing at ~ 1.3 T

* Watts of loss per pound of core steel are only comparable at the same magnetic flux density (measured in Tesla).

5.3.3 Core Configurations

In addition to selecting a core steel, the manufacturer's selection of a core design may also contribute to the overall efficiency of a transformer. A transformer facility may be optimized to work around one or two core configurations. Table 5.3.4 provides a list of all the core configurations used for each of the 13 design lines. DOE selected these configurations, in combination with the range of core steels and winding materials, to represent the most common construction methods for these kVA ratings in the U.S. market.

Table 5.3.4 Core Configurations Used in Each Design Line

Design Line	# Phases	Core Configurations Used in the Engineering Analysis
DL1	1	Wound core - distributed gap; Shell-type
DL2	1	Wound core - distributed gap; Shell-type or core-type
DL3	1	Wound core - distributed gap; Shell-type or core-type
DL4	3	Wound core - distributed gap or symmetric core; 5-leg
DL5	3	Wound core - distributed gap or symmetric core; 5-leg
DL6	1	Wound core – distributed gap; or stacked butt-lap; Shell-type or core-type
DL7	3	Wound core - distributed gap or symmetric core; or stacked, butt-lap or full mitered; 3-leg or 5-leg
DL8	3	Wound core - distributed gap or symmetric core; or stacked, butt-lap or full mitered; 3-leg or 5-leg
DL9	3	Wound core - distributed gap or symmetric core; or stacked full mitered; 3-leg or 5-leg
DL10	3	Wound core – distributed gap or symmetric core; or stacked, cruciform, mitered joint; 3-leg
DL11	3	Wound core – distributed gap or symmetric core; or stacked full mitered; 3-leg or 5-leg
DL12	3	Wound core – distributed gap or symmetric core; or stacked, cruciform, mitered joint; 3-leg or 5-leg
DL13	3	Wound core – distributed gap or symmetric core; or stacked, cruciform, mitered joint; 3-leg or 5-leg

5.3.3.1 Standard Core Configurations

For the single-phase representative units, the configurations used are either core-type or shell-type. This applies whether the core consists of stacked or wound laminations of core steel.

For wound cores, manufacturers generally employ a technique known as 'distributed gap.' This means that each lamination of core steel wound around the form will have a start and finish point (the 'gap'), staggered with respect to the previous and the next lamination. Distributed gap core construction techniques are used to minimize the performance impact of the lamination joint gaps (reducing the exciting current) and, by locating inside the coil window, reduce the transformer's operating sound level. Figure 5.3.2 illustrates the two types of single-phase core construction.

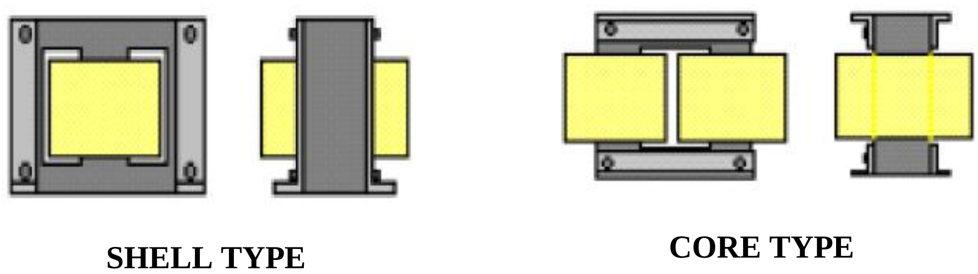

Figure 5.3.2 Graphic of Single-Phase Core Configurations

Three-phase transformers can have three-legged, four-legged, five-legged, Evans, or symmetric cores. In the engineering analysis, DOE considered the three-legged construction techniques for the three-phase dry-types and five-legged construction for the three-phase liquid-immersed transformers. Some of the dry-type designs using an amorphous core also use a five-legged construction technique. Figure 5.3.3 below illustrates the difference between the three-legged and the five-legged core construction techniques. A three-legged core is assembled from stacked laminations, the joints of which can be butt-lapped or mitered. Where there is an economic need to reduce core losses, particularly in keeping with the use of more efficient grades of core steel (M2 or M3), the mitered core tends to be selected. DOE recognizes that there are a variety of approaches to mitered core construction: "scrapless T-mitering," "full-mitering," and "step-mitering." DOE modeled full-mitered cores.

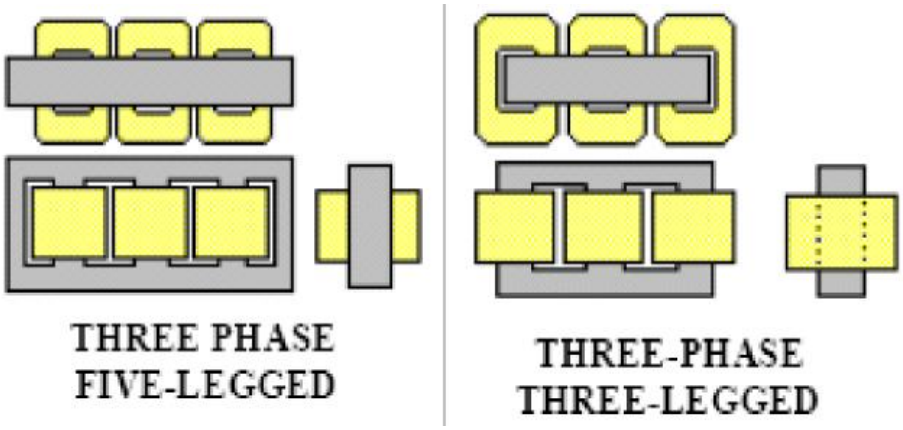

Figure 5.3.3 Graphic of Three-phase Core Configurations

For larger kVA ratings, design economics may cause the selection of a cruciform core section, where multiple lamination widths are stacked in increasing and then decreasing widths to create a circular core form (or "log") around which the windings are placed. Figure 5.3.4 illustrates the cruciform core by showing a cross-section. This figure shows four different widths of steel being used, but there can be fewer or more widths, depending on the design. By using a core configuration that better follows the contours of the windings, losses are again reduced, resulting in a more efficient transformer. The use of the three-legged core usually depends on the primary winding being delta-connected. If the primary winding is wye-connected, as is frequently the case for pad-mounted transformers used in underground distribution, the core configuration needs to be four-legged or five-legged.

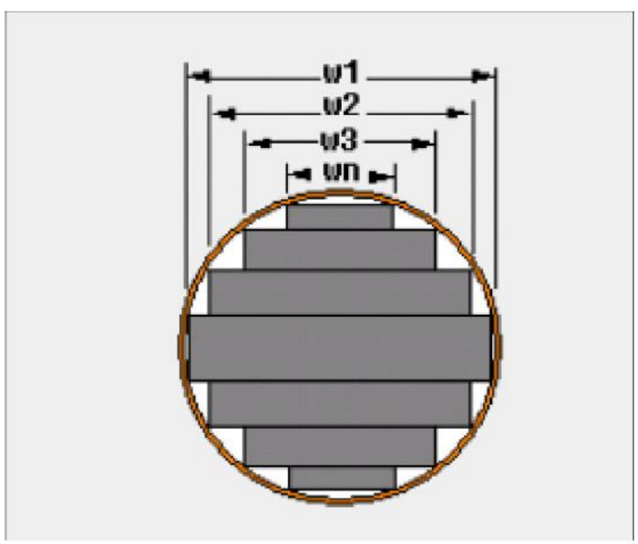

Figure 5.3.4 Cruciform Core Cross-Section

The five-legged core is assembled from four wound-core loops, and is the common configuration for liquid-filled, three-phase distribution transformers having a wye-wye voltage connection. Again, this occurs for pad-mounted transformers used in underground distribution.

The individual core loops have distributed gaps, as explained for single-phase, wound-core transformers.

5.3.3.2 Symmetric Core Configurations

In a symmetric core configuration, each leg of a three-phase transformer is identically connected to the other two. It uses a continuously wound core with 120˚ radial symmetry, resulting in a triangularly shaped core when viewed from above. In a traditional core, the center leg is magnetically distinguishable from the other two because it has a shorter average flux path to each. In a symmetric core, however, no leg is magnetically distinguishable from the other two. Figure 5.3.5 shows the configuration of the symmetric core design.[2]

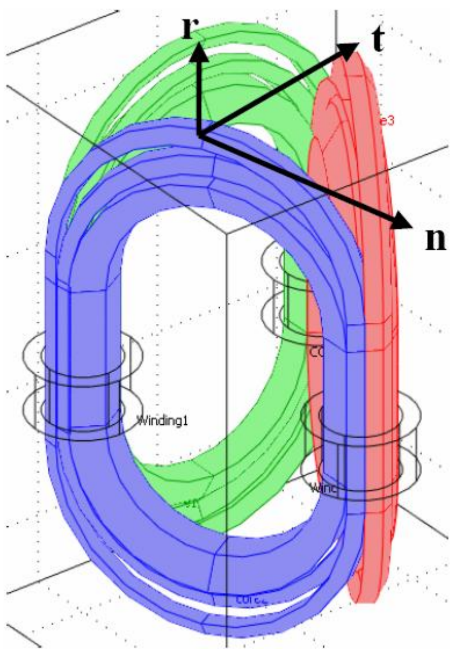

Figure 5.3.5 Graphic of Symmetric Core Configuration

The symmetric core construction offers several advantages over traditional transformer cores. These include lowered weight, volume, no-load losses, noise, vibration, stray magnetic fields, inrush current, and power in the third harmonic. Transformers using this core construction can oftentimes use less pounds of core steel than a standard core would use to achieve a given efficiency. As a result, total material cost for symmetric core designs is typically lower than a standard transformer design. However, the advanced manufacturing processes

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[2] Lundmark, Sonja. *Computer Model of Electromagnetic Phenomena in Hexaformer*. 2007. Available at: http://www.hexaformer.com/ExternaDokument/chalmers_report1.pdf.

necessary to produce the core increases the cost of labor and overhead for this core configuration. Similarly, the appropriate equipment requires large capital expenditures to manufacture this core type.

Because of zero-sequence fluxes associated with wye-wye connected transformers, symmetric core designs are best suited to delta-delta or delta-wye connections. While traditional cores can circumvent the problem of zero-sequence fluxes by introducing a fourth or fifth unwound leg, core symmetry makes extra legs inherently impractical. Yet another way to mitigate zero-sequence fluxes comes in the form of a tertiary winding, which is delta-connected and has no external connections. This winding is dormant when the transformer's load is balanced across its phases. Although symmetric core designs may, in theory, be made tolerant of zero-sequence fluxes by employing this method, it comes at extra cost and complexity.

Using this tertiary winding, DOE believes that symmetric core designs can service nearly all distribution transformer applications in the United States. Most dry-type transformers have a delta connection and would not require a tertiary winding. Similarly, most liquid-immersed transformers serving the industrial sector have a delta connection. These market segments could use the symmetric core design without any modification for a tertiary winding. However, in the United States most utility-operated distribution transformers are wye-wye connected. These transformers would require the tertiary winding in a symmetric core design.

DOE was unable to identify a company with commercial modeling software that could model symmetric core designs, but DOE did speak with many transformer manufacturers and industry experts about symmetric core designs. Through these conversations, DOE received information on a few symmetric core designs. These designs were insufficient to conduct a full-scale engineering analysis comparable to the other design types. However, DOE was able to approximate the cost-efficiency relationship for symmetric core designs based on trends in the data received from manufacturers, published literature, and through conversations with industry experts.

For each three-phase design line, DOE adjusted its traditional core designs to simulate a symmetric core design. To simulate the symmetric core design, DOE adjusted core losses, core weight, and labor costs. While these adjustments are rough approximations, they represent potential symmetric core designs for each design line.

To adjust core losses, DOE considered several symmetric core designs, conversations with manufacturers, and published literature. When examining the symmetric core data provided by manufacturers, DOE found that core losses for symmetric core designs range from 0 – 23 percent less than the core losses of comparable traditional transformers. This aligns with literature published by Chalmers University, which claims that core losses can be reduced by up to 25 percent using symmetric cores.[3] Using this data, DOE reduced core losses by 15.5 percent for its simulated symmetric core designs, which is the mean reduction from the examined data.

[3] "Comparison Between Hexa- and Conventional E-type Core Three-Phase Transformers." Available at: http://publications.lib.chalmers.se/cpl/record/index.xsql?pubid=74554.

DOE did not adjust the coil losses for the symmetric core designs compared to the traditional core designs.

In addition to reducing core losses, DOE reduced the core weight in the simulated symmetric core designs. Chalmers University literature estimates that symmetric cores reduce the total transformer weight by 12 percent.[3] Manufacturer designs show a reduction in core weight of 15 – 25 percent compared to traditional transformer designs. Relying on these data sources, DOE reduced core weight by 17.5 percent for the simulated symmetric core designs, which is the mean reduction from the examined data.

DOE's research indicates that labor costs would increase for symmetric core designs compared to the labor requirements for comparable traditional transformer designs. From speaking with manufacturers and examining symmetric core designs, DOE noted that labor costs may increase by 10 – 100 percent compared to the labor costs of traditional transformer designs. DOE increased the labor costs of its simulated symmetric core designs by 55 percent, which is the midpoint between the 10 percent and 100 percent estimates.

Table 5.3.5 identifies the adjustments DOE used to simulate the symmetric core designs. DOE applied these adjustments to each of the traditional three-phase transformer designs to develop a cost-efficiency relationship for symmetric core technology. DOE did not model a tertiary winding for the wye-wye connected liquid-immersed design lines. Based on its research, DOE believes that the losses associated with the tertiary winding may offset the benefits of the symmetric core design while also adding costs to the design. Instead, DOE modeled symmetric core designs for the three-phase, liquid-immersed design lines without a tertiary winding to examine the impact of symmetric core technology on the subgroup of applications that do not require the tertiary winding.

Table 5.3.5 Design Adjustments for Simulated Symmetric Core Designs

Range	**Core Losses [*W*] (*% Reduction*)**	**Core Weight [*lbs*] (*% Reduction*)**	**Labor Hours (*% Increase*)**
Minimum	-0.0	-12.0	+10
Mean of Observations	-15.5	-17.5	+55
Maximum	-25.0	-25.0	+100

Section 5.6 presents cost-efficiency results for the simulated symmetric core designs. For each three-phase design line, DOE considered an additional CSL to characterize the maximum efficiency available using symmetric core technology.

5.3.3.3 Core Deactivation Technology

Core deactivation technology employs a system of smaller transformers to replace a single, larger transformer. For example, three transformers sized at 25 kVA and operated in parallel could replace a single 75 kVA transformer. The smaller transformers that compose the system can then be activated and deactivated using core deactivation technology based on the loading demand.

Winding losses are proportionally smaller at lower load factors, but for any given current, a smaller transformer will experience greater winding losses than a larger transformer. As a result, those losses may be more than offset by the smaller transformer's reduced core losses. As loading increases, winding losses become proportionally larger and eventually outweigh the power saved by using the smaller core. At that point, the control unit (which consumes little power itself) switches on an additional transformer, reducing winding losses at the cost of additional core losses. The control unit knows how efficient each combination of transformers is for any given loading, and is constantly monitoring the unit's power output so that it will use the optimal number of cores. In theory, there is no limit to the number of transformers that may be paralleled in this sort of system, but cost considerations would imply an optimal number.

While core deactivation could save energy over a real world loading cycle, those savings might not be represented in the current DOE test procedure. Presently, the test procedure specifies a single loading point of 50 percent for liquid-immersed and medium-voltage dry-type transformers, and 35 percent for low-voltage dry-type. The real gain in efficiency for this technology is at loading points below the root mean square (RMS) loading specified in the test procedure, where some transformers in the system could be deactivated. At loadings where all transformers are activated, which may be the case at the test procedure loading, the combined core and coil losses of the system of transformers could exceed those of a single, larger transformer. This would result in a lower efficiency for the system of transformers compared to the single, larger transformer.

Therefore, DOE believes core deactivation technology may be at a disadvantage in the market based on the current test procedure, which specifies a single loading based on the RMS loading in the United States. DOE believes that the core deactivation system would engage all transformers at this loading, resulting in a lower efficiency reading than a standard, single transformer of equivalent size. However, the core deactivation system may save more energy than the standard transformer when all loading points that are experienced in service are considered. This is especially true for applications that have an average loading below the test procedure loading point.

DOE has not currently analyzed this technology in the engineering analysis or downstream analyses, but believes it could do so using its existing transformer designs. To analyze this technology, DOE would consider core deactivation systems composed of three identical transformers, each with one-third the kVA size of the analyzed design lines. This creates a core deactivation system of the same total kVA size as the analyzed design lines. Each of these core deactivation systems could be evaluated under various loading scenarios to identify the energy savings potential at loadings below and above the RMS load factor. While it is possible to manufacture core deactivation systems using different designs for each component transformer, it requires additional design complexities. For example, using different component transformer designs necessitates a similar winding design to maintain the impedance across each transformer at each load factor. These complexities would not need to be considered in the analysis when analyzing three identical component transformer designs.

To examine each component transformer design, DOE could scale the engineering analysis of its existing design lines to simulate a transformer of one-third the kVA size. DOE would scale the losses, manufacturer selling price (MSP), weight, and dimensions using the 0.75 scaling rule explained in section 5.2.2. The resulting designs could be analyzed as component transformers for the core deactivation system. DOE could then simulate a core deactivation system by combining three identical component transformers and considering the losses at each loading point for the following three scenarios: (1) all three component transformers are activated, (2) two component transformers are activated, and (3) only one component transformer is activated. Given this information, DOE could simulate the performance of a core deactivation system by evaluating the scenario with the least losses for a given load factor.

Additionally, DOE would account for the added cost and weight of the core deactivation technology. The additional components include items such as contactors, current sensors, a programmable logic controller, circuit boards, additional wiring, and other miscellaneous items. DOE estimated the cost of these components for a medium to large transformer manufacturer, and also estimated the incremental weight added by the components. Table 5.3.6 outlines the estimated cost and weight of the core deactivation components.

Table 5.3.6 Core Deactivation Technology Components, Cost and Weight

	Design Line 6	Design Line 7	Design Line 8
Core Deactivation Controller Cost	140	179	307
Other Components Cost [$]	237	312	882
Total Weight [lbs.]	22	50	141

DOE understands that core deactivation technology is most easily implemented in low-voltage dry-type distribution transformer designs. Implementing core deactivation technology in medium-voltage distribution transformers is possible, but poses difficulties for switching the primary and secondary connections. DOE has not fully quantified these differences, but intends to examine core deactivation technology in more detail for all types of transformers during the analysis for the notice of proposed rulemaking.

5.3.4 Less-Flammable Liquid-Immersed Transformers

For liquid-immersed distribution transformers, DOE studied the differences between mineral oil cooled units and less-flammable cooled units. DOE understands that the IEEE standard C57.12.80 divides less-flammable liquid-immersed (LFLI) transformers into two groups: KNAN (which have an insulating liquid with a fire point greater than 300 degrees Celsius) and LNAN (which have an insulating liquid with no measurable fire point). The fire point for mineral oil is approximately 175 degrees Celsius, and therefore this type of transformer is not used inside buildings or in areas designated as hazardous. While industry has a specification for KNAN for a certain degree of fire protection or LNAN for users who prefer an extra measure of safety, DOE will continue to refer to both KNAN and LNAN using the phrase ‘less-flammable,’ or LFLI.

DOE understands that the viscosity of the insulating liquid can have a slight impact on the efficiency of a transformer. When the viscosity is higher than mineral oil, transformer designers must make slightly larger cooling ducts to permit an easier flow of the fluid. Larger ducts result in larger physical size of the winding assembly, greater mean turn of the conductor, and therefore contribute to a slightly higher load loss. However, as efficiency increases, the transformer will run cooler, which negates part of the need for larger cooling ducts. As such, LFLI transformers are still able to achieve the same efficiency levels as transformers using mineral oil. DOE verified this fact through conversations with manufacturers and industry experts. In fact, DOE was informed that LFLI transformers might be capable of higher efficiencies than mineral oil units since their higher temperature tolerance may allow the unit to be downsized and run hotter than mineral oil units.

For the KNAN transformers (i.e., those with a fire point of 300 degrees or greater), DOE is not aware of any viscosity differences with mineral oil that might impede designs or make efficiency levels significantly more difficult to reach. For LNAN transformers (i.e., those with no fire point), DOE understands that the viscosity under usual operating conditions is slightly greater than that of mineral oil, which may require design engineers to increase the duct size, leading to a marginal impact on efficiency. However, as explained above, DOE believes this increased viscosity is offset by the cooler operating temperature, which could allow the transformer to be downsized and run hotter. This would negate any impact on efficiency. Chapter 2 provides additional discussion of less-flammable liquid-immersed transformers.

5.3.5 Design Line 1 Representative Unit

Design line 1 (DL1) represents rectangular-tank, liquid-immersed, single-phase distribution transformers, ranging from 10 kVA to 167 kVA. The representative unit selected for this design line is a 50kVA pad-mounted unit. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 50 (liquid-immersed, rectangular-tank)
Primary: 14400 Volts at 60 Hz
Secondary: 240/120V
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi-Lo (Shell-Type)
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 1.0–3.5 percent

For DL1, DOE selected six construction combinations (called "design option combinations"), based on input from manufacturers and other technical experts. The core selected was shell-type, because the application is for a pad-mounted unit, and this shape is well suited to a rectangular tank. With the exception of the max-tech/high efficiency designs, DOE selected six design option combinations to represent the most common construction practices for this representative unit.

Table 5.3.7 Design Option Combinations for the Representative Unit from Design Line 1

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M5	Cu – wire	Al – strip	Shell – DG* Wound Core
M3	Al – wire	Al – strip	Shell – DG Wound Core
M3	Cu – wire	Al – strip	Shell – DG Wound Core
M2	Cu – wire	Al – strip	Shell – DG Wound Core
ZDMH	Cu – wire	Cu – strip	Shell – DG Wound Core
SA1 (Amorphous)	Cu – wire	Cu – strip	Shell – DG Wound Core

* DG – Distributed gap wound core construction, where the core laminations are wound in such a way that the gap between the start and finish of a lamination is staggered in the cross-section of the core.

DOE analyzed each of the six design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,382 designs.

5.3.6 Design Line 2 Representative Unit

Design line 2 (DL2) represents round-tank, liquid-immersed, single-phase distribution transformers, ranging from 10 kVA to 167 kVA. The representative unit selected for this design line is a 25kVA pole-mounted unit. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 25 (liquid-immersed, round-tank)
Primary: 14400 Volts at 60 Hz (125 kV BIL)
Secondary: 120/240V
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi-Lo (Shell-Type), Lo-Hi (Core-Type, for amorphous core)
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 1.0–3.5 percent

For DL2, DOE selected seven design option combinations, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practices for the representative unit.

Table 5.3.8 Design Option Combinations for the Representative Unit from Design Line 2

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M5	Cu – wire	Al – strip	Shell – DG Wound Core
M4	Al – wire	Al – strip	Shell – DG Wound Core
M4	Cu – wire	Al – strip	Shell – DG Wound Core
M3	Cu – wire	Al – strip	Shell – DG Wound Core
M2	Cu – wire	Al – strip	Shell – DG Wound Core
ZDMH	Cu – wire	Cu – strip	Shell – DG Wound Core
SA1 (Amorphous)	Cu – wire	Cu – strip	Core – DG Wound Core

DOE analyzed each of the seven design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,509 designs.

5.3.7 Design Line 3 Representative Unit

Design line 3 (DL3) represents round-tank, liquid-immersed, single-phase distribution transformers, ranging from 250 kVA to 833 kVA. The representative unit selected for this design line is a 500kVA round-tank transformer. The following are the technical specifications which constitute input parameters to the OPS design software:

KVA: 500 (liquid-immersed, round-tank)
Primary: 14400 Volts at 60 HZ (150kV BIL)
Secondary: 277 Volts
T Rise: 65˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi (Shell-Type and Core-Type)
Core: Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 2.5–5.75 percent

For DL3, DOE selected seven design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE chose design option combinations to represent the most common construction practice for this representative unit.

Table 5.3.9 Design Option Combinations for the Representative Unit from Design Line 3

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M5	Cu – wire	Al – strip	Shell – DG Wound Core
M4	Cu – wire	Al – strip	Shell – DG Wound Core
M3	Cu – wire	Al – strip	Shell – DG Wound Core
M2	Cu – wire	Al – strip	Shell – DG Wound Core
ZDMH	Cu – wire	Cu – strip	Shell – DG Wound Core
SA1 (Amorphous)	Cu – wire	Cu – strip	Shell – DG Wound Core
SA1 (Amorphous)	Cu – wire	Cu – strip	Core – DG Wound Core

DOE analyzed each of the seven design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,486 designs.

5.3.8 Design Line 4 Representative Unit

Design line 4 (DL4) represents rectangular tank, liquid-immersed, three-phase distribution transformers, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 150kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 150 (liquid-immersed, pad mount)
Primary: 12470Y/7200 Volts at 60 Hz (95kV BIL)
Secondary: 208Y/120 Volts
T Rise: 65˚C
Ambient: 20˚C
Terminal Configuration: ANSI/IEEE C57.12.26, Loop Feed
Winding Configuration: Lo-Hi
Core: Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 1.5–3.0 percent

For DL4, DOE selected five design option combinations of core steel and winding types based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.10 Design Option Combinations for the Representative Unit from Design Line 4

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M5	Cu – wire	Al – strip	5-Leg DG Core
M3	Cu – wire	Al – strip	5-Leg DG Core
M2	Cu – wire	Al – strip	5-Leg DG Core
ZDMH	Cu – wire	Cu – strip	5-Leg DG Core
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

DOE analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,101 designs.

5.3.9 Design Line 5 Representative Unit

Design line 5 (DL5) represents rectangular tank, liquid-immersed, three-phase distribution transformers, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 1500 (liquid-immersed, pad mount)
Primary: 24940GrdY/14400 Volts (125kV BIL)
Secondary: 480Y/277 Volts
T Rise: 65˚C
Ambient: 20˚C
Terminal Configuration: ANSI/IEEE C57.12.26, Loop Feed
Winding Configuration: Lo-Hi
Core: Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 4.5-7.0 percent

For DL5, DOE selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practices for the representative unit.

Table 5.3.11 Design Option Combinations for the Representative Unit from Design Line 5

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M4	Cu – wire	Al – strip	5-Leg DG Core
M3	Cu – wire	Al – strip	5-Leg DG Core
M2	Cu – wire	Al – strip	5-Leg DG Core
ZDMH	Cu – wire	Cu – strip	5-Leg DG Core
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

DOE analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,074 designs.

5.3.10 Design Line 6 Representative Unit

Design line 6 (DL6) represents ventilated dry-type, single-phase, low-voltage distribution transformers, ranging from 15 kVA to 333 kVA. The representative unit selected for this design line is a 25 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 25 (dry-type)
Phases: Single
Primary: 480 Volts at 60 Hz (10 kV BIL)
Secondary: 120/240 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi (for Core-Type and Shell-Type)
Core: Stacked, butt-lap; Wound core - distributed gap
Taps: Six 2½ percent, two above and four below the nominal
Impedance Range: 3.0–6.0 percent

For DL6, DOE selected six design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.12 Design Option Combinations for the Representative Unit from Design Line 6

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Al – wire	Al – wire	Stacked Core Butt-lap
M4	Al – wire	Al – wire	Stacked Core Butt-lap
M3	Cu – wire	Al – wire	Stacked Core Butt-lap
M3	Cu – wire	Al – wire	Stacked Shell Butt-lap
H-0 DR*	Cu – wire	Cu – wire	Stacked Core Butt-lap
SA1 (Amorphous)	Cu – wire	Cu – wire	Core – DG Wound Core

* H-0 DR is a domain-refined, high permeability core steel.

DOE analyzed each of the six design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 2,455 designs.

5.3.11 Design Line 7 Representative Unit

Design line 7 (DL7) represents ventilated dry-type, three-phase, low-voltage distribution transformers, ranging from 15 kVA to 150 kVA. The representative unit selected for this design line is a 75 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 75 (dry-type)
Phases: Three
Primary: 480 Volts at 60 Hz (10 kV BIL)
Secondary: 208Y/120 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, butt-lap; Stacked, mitered; Wound core - distributed gap
Taps: Six 2½ percent, two above and four below the nominal
Impedance Range: 1.5–6.0 percent

For DL7, DOE selected eight design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.13 Design Option Combinations for the Representative Unit from Design Line 7

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M12	Al – wire	Al – wire	3-Leg Stacked Butt-lap
M12	Cu – wire	Al – wire	3-Leg Stacked Butt-lap
M6	Al – wire	Al – wire	3-Leg Stacked Butt-lap
M6	Al – wire	Al – wire	3-Leg Stacked Full Miter**
M4	Cu – wire	Al – wire	3-Leg Stacked Full Miter
M3	Al – wire	Al – wire	3-Leg Stacked Full Miter
H-0 DR*	Cu – wire	Cu – wire	3-Leg Stacked Full Miter
SA1 (Amorphous)	Cu – wire	Cu – wire	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.

** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

DOE analyzed each of the eight design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 2,765 designs.

5.3.12 Design Line 8 Representative Unit

Design line 8 (DL8) represents ventilated dry-type, three-phase, low-voltage distribution transformers, ranging from 225 kVA to 1000 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 300 (dry-type)
Phases: Three
Primary: 480V at 60 Hz (10 kV BIL) Delta Connected
Secondary: 208Y/120 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, butt-lap; Stacked, mitered; Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 3.0–6.0 percent

For DL8, DOE selected eight design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.14 Design Option Combinations for the Representative Unit from Design Line 8

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Al – wire	Al – strip	3-Leg Stacked Butt-lap
M6	Cu – wire	Cu – strip	3-Leg Stacked Full Miter**
M5	Al – wire	Al – strip	3-Leg Stacked Butt-lap
M5	Al – wire	Al – strip	3-Leg Stacked Full Miter
M4	Cu – wire	Al – strip	3-Leg Stacked Full Miter
M3	Cu – wire	Al – strip	3-Leg Stacked Full Miter
H-0 DR*	Cu – wire	Cu – strip	3-Leg Stacked Full Miter
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.
** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

DOE analyzed each of the eight design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 3,074 designs.

5.3.13 Design Line 9 Representative Unit

Design line 9 (DL9) represents ventilated dry-type, three-phase, medium-voltage distribution transformers with a 20-45kV BIL, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 300 (dry-type)
Phases: Three
Primary: 4160V at 60 Hz (45 kV BIL) Delta Connected
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, mitered; Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 3.0–6.0 percent

For DL9, DOE selected six design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.15 Design Option Combinations for the Representative Unit from Design Line 9

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Cu – wire	Cu – wire	3-Leg Stacked Full Miter**
M5	Al – wire	Al – wire	3-Leg Stacked Full Miter
M3	Cu – wire	Al – strip	3-Leg Stacked Full Miter
H-0 DR*	Cu – wire	Cu – strip	3-Leg Stacked Full Miter
SA1 (Amorphous)	Cu – wire	Cu – strip	3-Leg DG Core
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.
** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

DOE analyzed each of the six design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 2,754 designs.

5.3.14 Design Line 10 Representative Unit

Design line 10 (DL10) represents dry-type, three-phase, medium-voltage distribution transformers with a 20-45kV BIL, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 1500 (dry-type)
Phases: Three
Primary: 4160V at 60 Hz (45 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, cruciform, mitered joint, 3-leg; Wound core - distributed gap
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 5.0-7.0 percent

For DL10, DOE selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.16 Design Option Combinations for the Representative Unit from Design Line 10

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M5	Cu – wire	Al – strip	3-Leg Mitered Cruciform
M4	Cu – wire	Al – strip	3-Leg Mitered Cruciform
M3	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
H-0 DR*	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
SA1 (Amorphous	Cu – wire	Cu – strip	3-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.

DOE analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,263 designs.

5.3.15 Design Line 11 Representative Unit

Design line 11 (DL11) represents dry-type, three-phase, medium-voltage distribution transformers with a 46-95kV BIL, ranging from 15 kVA to 500 kVA. The representative unit selected for this design line is a 300 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 300 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (95 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, mitered joint, 3-leg; Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 3.0-7.0 percent

For DL11, DOE selected five design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.17 Design Option Combinations for the Representative Unit from Design Line 11

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Cu – wire	Cu – strip	3-Leg Stacked Full Miter**
M4	Cu – wire	Al – strip	3-Leg Stacked Full Miter
M3	Cu – wire	Cu – strip	3-Leg Stacked Full Miter
H-0 DR*	Cu – wire	Cu – strip	3-Leg Stacked Full Miter
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.
** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

DOE analyzed each of the five design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 990 designs.

5.3.16 Design Line 12 Representative Unit

Design line 12 (DL12) represents dry-type, three-phase, medium-voltage distribution transformers with a 46-95kV BIL, ranging from 750 kVA to 2500 kVA. The representative unit selected for this design line is a 1500 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 1500 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (95 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, cruciform, mitered joint, 3-leg; Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below the nominal
Impedance Range: 5.0–8.0 percent

For DL12, DOE selected six design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.18 Design Option Combinations for the Representative Unit from Design Line 12

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Al – wire	Al – strip	3-Leg Mitered Cruciform
M5	Al – wire	Al – strip	3-Leg Mitered Cruciform
M4	Cu – wire	Al – strip	3-Leg Mitered Cruciform
M3	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
H-0 DR*	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.

DOE analyzed each of the six design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 1,779 designs.

5.3.17 Design Line 13 Representative Unit

Design line 13 (DL13) represents dry-type, three-phase, medium-voltage distribution transformers with a ≥96kV BIL, ranging from 225 kVA to 2500 kVA. The representative unit selected for this design line is a 2000 kVA transformer. The following are the technical specifications that constitute input parameters to the OPS design software:

KVA: 2000 (dry-type)
Phases: Three
Primary: 12470 Volts at 60 Hz (125 kV BIL)
Secondary: 480Y/277 Volts
T Rise: 150˚C
Ambient: 20˚C
Winding Configuration: Lo-Hi
Core: Stacked, cruciform, mitered joint, 3-leg; Wound core - distributed gap, 5-leg
Taps: Four 2½ percent, two above and two below the nominal

Impedance Range: 4.0–7.0 percent

For DL13, DOE selected seven design option combinations of core steel and winding material, based on input from manufacturers and other technical experts. With the exception of the max-tech/high-efficiency designs, DOE selected these design option combinations to represent the most common construction practice for the representative unit.

Table 5.3.19 Design Option Combinations for the Representative Unit from Design Line 13

Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
M6	Al – wire	Al – strip	3-Leg Mitered Cruciform
M6	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
M5	Al – wire	Al – strip	3-Leg Mitered Cruciform
M4	Cu – wire	Al – strip	3-Leg Mitered Cruciform
M3	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
H-0 DR*	Cu – wire	Cu – strip	3-Leg Mitered Cruciform
SA1 (Amorphous)	Cu – wire	Cu – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.

DOE analyzed each of the seven design option combinations using the matrix of A and B values described in Table 5.3.1 and Table 5.3.2, creating 2,349 designs.

5.3.18 Newly Optimized Designs and Previously Optimized Designs

DOE utilized a combination of newly optimized design runs and designs that were optimized during the previous rulemaking for distribution transformers. For each design option combination chosen, DOE generates designs based on 518 A and B factor combinations. These A and B factor combinations cover the spectrum of typical load loss and no-load loss valuations, generating a unique design across a range of efficiencies.

DOE understands that typically a design would be optimized based on the current material prices. Optimizing a design based on historical material prices may result in a differently optimized design, such as a design that utilizes relatively more conductor than core. However, DOE believes that it adequately covered the spectrum of possible designs for each design option combination used in the previous rulemaking based on the large sample of A and B factor combinations considered for each design option combination. As such, DOE believes that these designs are still valid when updated material prices are applied to them.

DOE updated the cost of these previous design runs by applying updated prices to the design's bill of materials. Effectively, DOE calculated the present cost of developing the same design that was used in the previous rulemaking. DOE also updated labor prices and applied the markups consistently with any newly optimized designs generated for the analysis.

While DOE believes that its approach of reusing previously optimized designs with updated material prices is reasonable, it plans to create newly optimized designs for the analysis as well. Currently, DOE has added in several new design option combinations, which are modeled with a newly optimized design. Additionally, DOE may choose to re-optimize the designs from the previous rulemaking rather than simply updating their material prices as the analysis progresses.

5.3.19 Supplemental Designs Using Aluminum Conductors

DOE examined several additional design option combinations for each design line. These design option combinations examine alternate pathways to achieve a given efficiency level. During preliminary interviews with manufacturers, DOE was informed that its analysis should consider more design option combinations that use aluminum conductors, which have become increasingly popular compared to copper conductors due to increases in the price of copper. In response, DOE modeled several additional design option combinations. These design option combinations were not prepared in time for DOE to analyze them as part of its LCC or national impacts analyses (NIA), so DOE presents them as a separate set of designs. The design option combinations considered for the LCC and NIA are presented in sections 5.3.5 through 5.3.17.

Table 5.3.20 through Table 5.3.22 presents the supplemental design option combinations using aluminum conductors that DOE modeled for each design line. Each of these design option combinations were newly optimized using the material prices outlined in sections 5.4.2 and 5.4.3.

Table 5.3.20 Supplemental Design Option Combinations, Liquid-Immersed

Design Line	Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
1	M2	Al – wire	Al – strip	Shell – DG Wound Core
	ZDMH	Al – wire	Al – strip	Shell – DG Wound Core
	SA1 (Amorphous)	Al – wire	Al – strip	Shell – DG Wound Core
2	M3	Al – wire	Al – strip	Shell – DG Wound Core
	M2	Al – wire	Al – strip	Shell – DG Wound Core
	ZDMH	Al – wire	Al – strip	Shell – DG Wound Core
	SA1 (Amorphous)	Al – wire	Al – strip	Core – DG Wound Core
3	M4	Al – wire	Al – strip	Shell – DG Wound Core
	M3	Al – wire	Al – strip	Shell – DG Wound Core
	M2	Al – wire	Al – strip	Shell – DG Wound Core
	ZDMH	Al – wire	Al – strip	Shell – DG Wound Core
	SA1 (Amorphous)	Al – wire	Al – strip	Core – DG Wound Core
4	M3	Al – wire	Al – strip	5-Leg DG Core
	M2	Al – wire	Al – strip	5-Leg DG Core
	ZDMH	Al – wire	Al – strip	5-Leg DG Core
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
5	M3	Al – wire	Al – strip	5-Leg DG Core
	M2	Al – wire	Al – strip	5-Leg DG Core
	ZDMH	Al – wire	Al – strip	5-Leg DG Core
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core

Table 5.3.21 Supplemental Design Option Combinations, Low-Voltage Dry Type

Design Line	Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
6	M3	Al – wire	Al – strip	Stacked Core Butt-lap
	H-0 DR*	Al – wire	Al – strip	Stacked Core Butt-lap
	SA1 (Amorphous)	Al – wire	Al – strip	Core – DG Wound Core
7	H-0 DR	Al – wire	Al – strip	3-Leg Stacked Full Miter**
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
8	M3	Al – wire	Al – strip	3-Leg Stacked Full Miter
	H-0 DR	Al – wire	Al – strip	3-Leg Stacked Full Miter
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.
** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

Table 5.3.22 Supplemental Design Option Combinations, Medium-Voltage Dry-Type

Design Line	Core Material	High-Voltage Conductor	Low-Voltage Conductor	Core Design Type
9	M3	Al – wire	Al – strip	3-Leg Stacked Full Miter**
	H-0 DR*	Al – wire	Al – strip	3-Leg Stacked Full Miter
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
10	M3	Al – wire	Al – strip	3-Leg Mitered Cruciform
	H-0 DR	Al – wire	Al – strip	3-Leg Mitered Cruciform
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
11	M3	Al – wire	Al – strip	3-Leg Stacked Full Miter
	H-0 DR	Al – wire	Al – strip	3-Leg Stacked Full Miter
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
12	M3	Al – wire	Al – strip	3-Leg Mitered Cruciform
	H-0 DR	Al – wire	Al – strip	3-Leg Mitered Cruciform
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core
13	M3	Al – wire	Al – strip	3-Leg Mitered Cruciform
	H-0 DR	Al – wire	Al – strip	3-Leg Mitered Cruciform
	SA1 (Amorphous)	Al – wire	Al – strip	5-Leg DG Core

* H-0 DR is a domain-refined, high permeability core steel.
** Full miters are not step-miters, but are mitered joints for all three legs. These cores are stacked three by three.

The cost-efficiency relationship for each of these designs is presented in section 5.6.3. In that section, DOE presents figures showing the supplemental designs and the reference case designs plotted with manufacturer selling price vs. efficiency.

5.4 MATERIAL AND LABOR INPUTS

DOE uses a standard method of cost accounting with minor changes to determine the costs associated with manufacturing. This methodology is illustrated in Figure 5.4.1, where production costs and non-production costs are combined to determine the manufacturer's selling price of the equipment.

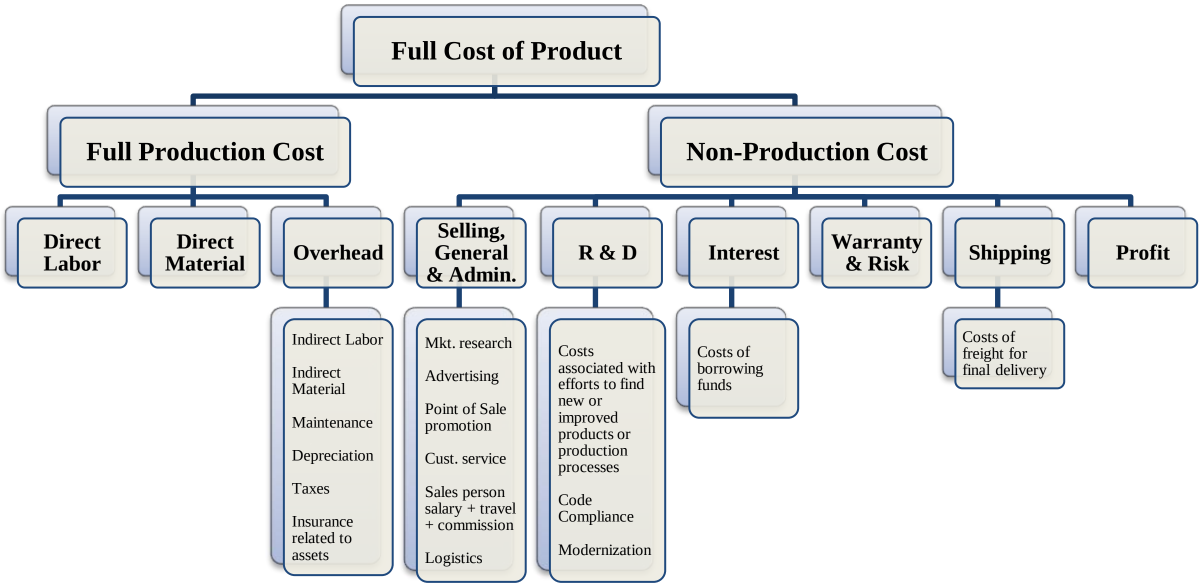

Figure 5.4.1 Method of Cost Accounting for Distribution Transformers Rulemaking

The full production cost and the non-production cost equal the manufacturer's selling price of the equipment. Full production cost is a combination of direct labor, direct materials, and overhead. The overhead contributing to full production cost includes indirect labor, indirect material, maintenance, depreciation, taxes, and insurance related to company assets. Non-production cost includes the cost of selling, general and administrative items (market research, advertising, sales representatives, logistics), research and development (R&D), interest payments, warranty and risk provisions, shipping, and profit factor. Because profit factor is included in the non-production cost, the sum of production and non-production costs is an estimate of the manufacturer's selling price.

DOE used several estimates of the costs listed in Figure 5.4.1 from DOE's previous rulemaking on distribution transformers, published in October 2007. The estimates from this rulemaking relied on U.S. Industry Census Data Reports, manufacturer interviews, and Securities and Exchange Commission (SEC) 10-K reports for several manufacturers. It then refined these estimates through meetings and dialogue with transformer manufacturers in 2010. The following markups resulted:

- Scrap and handling factor: 2.5 percent markup. This markup applies to variable materials (e.g., core steel, windings, insulation). It accounts for the handling of material (loading into assembly or winding equipment) and the scrap material that cannot be used in the production of a finished transformer (e.g., lengths of wire too short to wind, trimmed core steel).

- Amorphous scrap factor: 1.5 percent markup. This markup accounts for breakage of prefabricated amorphous cores and any scrap associated with assembling the windings on the core. Since amorphous cores are considered to be prefabricated, the regular scrap and handling factor is reduced.

- Mitered scrap factor: 4.0 percent markup. An additional scrap markup applies to steel used in full-mitered cores. This markup represents material cut from the notch in the yoke.

- Factory overhead: 12.5 percent markup. Factory overhead includes all the indirect costs associated with production, indirect materials and energy use (e.g., annealing furnace), taxes, and insurance. DOE only applied factory overhead to the direct material production costs.

- Shipping: $0.22 per pound for each transformer. The shipping costs include the freight from a manufacturer's facility to the customer. This shipping cost does not include any freight charges for the customer to subsequently move the transformer to its end-use location. DOE applied the shipping charge prior to applying the profit markup based on feedback from manufacturer interviews in 2010.

- Non-production: 25 percent markup. This markup reflects costs including selling, general and administrative, R&D, interest payments, warranty and risk provisions, and profit factor. DOE applied the non-production markup to the sum of direct material, direct labor, and factory overhead.

The following example shows how DOE applied the markups to the materials, and how it determined the manufacturer selling price. Consider a 300kVA 45kV BIL three-phase, dry-type transformer designed with a $1.50 A and a $0.30 B. This design has $4,839 of materials, including M6 core steel, copper primary and secondary windings, and all the transformer hardware. There are approximately 27 hours of labor involved in manufacturing this design, resulting in a labor cost of $1,367. The factory overhead on this design is $605, as it is only applied to the material cost (i.e., 12.5 percent of $4,839). The shipping cost is $394, based on a weight of 1,792 pounds. The non-production cost is $1,817, since the 25 percent is applied to the material, labor, factory overhead, and shipping costs (i.e., 25 percent of $4,839 + $1,367 + $605 + $394). Thus, in total, DOE estimates this 300kVA three-phase transformer to have a manufacturer selling price of $9,084.

5.4.1 Material Prices

DOE used prices of core steel, conductor, mineral oil, insulation, and other materials as an input to the transformer design software used for the engineering analysis. As the price of one material increases or decreases relative to the other materials, the software will modify its design and increase or decrease the amount of that material while balancing other design parameters, creating a cost-optimized transformer. Material pricing is also critical because the manufacturer's selling prices calculated in the engineering analysis are based on a bill of materials that includes specifications for pounds of steel, pounds of conductor, gallons of mineral oil, tank dimensions, and so on. Therefore, as material prices increase, so will the manufacturer's selling price. Furthermore, as discussed in Chapter 3, energy-efficient transformers tend to incorporate more materials (e.g., pounds of core steel, pounds of conductor), making the impact of more expensive materials even more significant at higher efficiencies.

DOE contracted OPS to develop material price estimates for the engineering analysis. OPS used data from their own records as well as data provided by transformer manufacturers and material suppliers and wholesalers. Although not all transformer manufacturers pay the same amount per pound for electrical-grade steels, due to varied contract negotiations, these prices are intended to be representative of a standard quantity order for a medium- to large-scale U.S. transformer manufacturer.

DOE conducted the engineering analysis using material prices over a five-year time period from 2006-2010, all in constant 2010$. Using the material prices from this time period, DOE considered a current (2010) material price, a minimum price (based on 2006 prices), and a maximum price (based on 2008 prices) for its analysis. This was done to account for variation in pricing for the different materials, which could have a significant impact on the total cost of the distribution transformer. All transformer designs that were newly optimized used the current 2010 material price, which DOE used as its reference case. The maximum and minimum prices were then applied to these same designs to generate a manufacturer selling price for each of those scenarios. The results of the current 2010 material prices are presented here in Chapter 5, while the results of the minimum and maximum material prices are presented in Appendix 5C.

DOE noted that the price of the most critical material input to a distribution transformer, electrical core steel, had varied significantly for some M-grades over the five-year time horizon (see Table 5.4.1). For this reason, DOE researched the grain-oriented electrical steel market to gain a better understanding of the main players and some of the factors influencing these price fluctuations (see Appendix 3A).

In the LCC analysis (Chapter 8), DOE presents results on its sensitivity analyses conducted on various LCC inputs, which included material prices. In Chapter 8, the 2008 material price scenario is referred to as the “high” price scenario, the 2010 price scenario is called the “medium” price scenario, and the 2006 material price scenario is referred to as the “low” price scenario. DOE chose to utilize the current 2010 material price in the reference case after receiving feedback from transformer manufacturers and suppliers of core steel indicating that current prices would be a better price indicator than a five-year average price. These material prices can be found in the material price tables presented in this section. The resulting manufacturer selling prices are provided in the LCC spreadsheets.

5.4.2 Material Inputs to the Design Software – Liquid-Immersed

Table 5.4.1 presents the material prices for a typical manufacturer of liquid-immersed transformers over the five-year 2006-2010 time horizon, indicating the current, minimum, and maximum prices (all in constant 2010$). The highlighted columns are the prices that DOE used in the engineering analysis.

Table 5.4.1 Typical Manufacturer's Material Prices for Liquid-Immersed Design Lines

Material	**Units**	**2010 Price** *2010$*	**2006 Price (Min.)** *2010$*	**2008 Price (Max.)** *2010$*	**2010** *2010$*	**2009** *2010$*	**2008** *2010$*	**2007** *2010$*	**2006** *2010$*
M6 core steel	*$/lb*	1.46	1.10	1.70	1.46	1.61	1.70	1.47	1.10
M5 core steel	*$/lb*	1.51	1.15	1.74	1.51	1.64	1.74	1.49	1.15
M4 core steel	*$/lb*	1.59	1.20	1.78	1.59	1.68	1.78	1.52	1.20
M3 core steel	*$/lb*	1.88	1.23	2.02	1.88	1.93	2.02	1.58	1.23
M3 core steel (Lite Carlite)	*$/lb*	1.95	0.00	0.00	1.95	0.00	0.00	0.00	0.00
M2 core steel	*$/lb*	2.00	1.54	2.16	2.00	1.98	2.16	2.02	1.54
M2 core steel (Lite Carlite)	*$/lb*	2.10	0.00	0.00	2.10	0.00	0.00	0.00	0.00
ZDMH (mechanically-scribed core steel)	*$/lb*	2.05	1.64	2.49	2.05	1.99	2.49	2.12	1.64
SA1 (amorphous) finished core, volume production	*$/lb*	2.38	0.00	2.82	2.38	2.26	2.82	0.00	0.00
Copper wire, formvar, round #10-20	*$/lb*	3.94	3.91	4.69	3.94	3.33	4.69	4.39	3.91
Copper wire, enameled, round #7-10	*$/lb*	4.35	4.35	4.82	4.35	3.48	4.82	4.52	4.35
Copper wire, enameled, rectangular sizes	*$/lb*	4.31	3.41	4.20	4.31	3.55	4.20	3.95	3.41
Aluminum wire, formvar, round #9-17	*$/lb*	3.65	2.32	2.71	3.65	2.55	2.71	2.40	2.32
Aluminum wire, formvar, round #7-10	*$/lb*	3.34	2.36	3.37	3.34	3.17	3.37	3.02	2.36
Copper strip, thickness range 0.02-0.045	*$/lb*	4.25	3.87	4.17	4.25	3.08	4.17	4.31	3.87
Copper strip, thickness range 0.030-0.060	*$/lb*	4.22	3.85	4.14	4.22	3.05	4.14	4.28	3.85
Aluminum strip, thickness range 0.02-0.045	*$/lb*	1.57	1.72	1.87	1.57	1.51	1.87	1.86	1.72
Aluminum strip, thickness range 0.045-0.080	*$/lb*	1.58	1.76	1.93	1.58	1.57	1.93	1.90	1.76
Kraft insulating paper with diamond adhesive	*$/lb*	1.52	1.36	1.49	1.52	1.52	1.49	1.45	1.36
Mineral oil	*$/gal*	3.35	2.26	2.97	3.35	2.85	2.97	2.33	2.26
Tank Steel	*$/lb*	0.38	0.38	0.47	0.38	0.38	0.47	0.40	0.38

DOE then marked up the raw material prices presented in Table 5.4.1 using the manufacturer's internal markups discussed in section 5.4.1. DOE used the marked-up material prices as inputs to the transformer design software for optimization, even though the material prices do not receive the markup during DOE's cost calculation. The cost calculation applies the markups to the total material cost. During its manufacturer site visits in 2010, DOE found this approach to be consistent with that of several manufacturers who operate their own, proprietary transformer design software. For example, a raw material price of $1.00/lb. would be marked up to $1.44/lb., reflecting the handling and scrap factor (2.5 percent), the factory overhead (12.5 percent), and the non-production markup (25 percent). DOE did not include shipping costs as a markup of the raw material because these costs were based on the weight of the design, not a percentage markup. Table 5.4.2 shows the markup steps being applied to the current 2010 material price scenario.

Table 5.4.2 Marked-up Material Prices for Liquid-Immersed Units, Current Year (2010) Price Scenario

Item and Description	Units	Current 2010 Price *2010$*	Scrap & Handling	Factory Overhead	Non-Production	Software Input
M6 core steel	$/lb	1.46	1.025	1.125	1.25	2.10
M5 core steel	$/lb	1.51	1.025	1.125	1.25	2.18
M4 core steel	$/lb	1.59	1.025	1.125	1.25	2.28
M3 core steel	$/lb	1.88	1.025	1.125	1.25	2.70
M3 core steel (Lite Carlite)	$/lb	1.95	1.025	1.125	1.25	2.82
M2 core steel	$/lb	2.00	1.025	1.125	1.25	2.88
M2 core steel (Lite Carlite)	$/lb	2.10	1.025	1.125	1.25	3.03
ZDMH (mechanically-scribed core steel)	$/lb	2.05	1.025	1.125	1.25	2.95
SA1 (amorphous) finished core, volume production	$/lb	2.38	1.015	1.125	1.25	3.40
Copper wire, formvar, round #10-20	$/lb	3.94	1.025	1.125	1.25	5.68
Copper wire, enameled, round #7-10	$/lb	4.35	1.025	1.125	1.25	6.27
Copper wire, enameled, rectangular sizes	$/lb	4.31	1.025	1.125	1.25	6.21
Aluminum wire, formvar, round #9-17	$/lb	3.65	1.025	1.125	1.25	5.26
Aluminum wire, formvar, round #7-10	$/lb	3.34	1.025	1.125	1.25	4.81
Copper strip, thickness range 0.02-0.045	$/lb	4.25	1.025	1.125	1.25	6.13
Copper strip, thickness range 0.030-0.060	$/lb	4.22	1.025	1.125	1.25	6.09
Aluminum strip, thickness range 0.02-0.045	$/lb	1.57	1.025	1.125	1.25	2.26
Aluminum strip, thickness range 0.045-0.080	$/lb	1.58	1.025	1.125	1.25	2.28
Kraft insulating paper with diamond adhesive	$/lb	1.52	1.025	1.125	1.25	2.18
Mineral oil	$/gal	3.35	-	1.125	1.25	4.71
Tank Steel	$/lb	0.38	1.025	1.125	1.25	0.55

The price used for a prefabricated amorphous core is based on prices of finished cores from North American manufacturers. In the previous rulemaking for distribution transformers, DOE analyzed the cost importing finished cores from overseas. Since that time, several North American core manufacturers have begun producing amorphous cores. For the preliminary analysis, DOE considered the price of a prefabricated amorphous core bought from a North American core manufacturer.

In addition to the aforementioned materials that vary during the design optimization process (e.g., core steel, windings, insulation), there are other direct materials inputs that are fixed costs and generally do not influence the design or vary with efficiency rating. These include direct materials, such as the high- and low-voltage bushings and the core clamps. DOE also prepared estimates of the tank fabrication cost, based on the optimized transformer design (the software considers this variable) and the labor necessary to build the tank. Table 5.4.3 summarizes all the estimated fixed material costs and estimates of the tank costs for each of the five liquid-immersed design lines.

For DL1, a 50kVA single-phase pad-mounted unit, the high-voltage bushings are two universal bushing wells, 15 kV, 95 BIL, 14400V, costing $7 each. The low-voltage bushings are three threaded copper studs, 240/120V, 50 kVA, costing $20 for the set. Internal hardware costs include a core clamp, nameplate, and other miscellaneous hardware costing $25.65. The finished tank size (and associated cost) varies by design, but the average is approximately $141.

For DL2, a 25kVA single-phase pole-mounted unit, the high-voltage terminal is a single, wet-process porcelain bushing assembly, 15 kV, 125 BIL, costing $6. The low-voltage terminals are three molded polymer bushings, 120/240V, 25 kVA, costing $8 for the set. Internal hardware costs include a core clamp, nameplate, and other miscellaneous hardware, costing $19.15. The finished tank sizes (height and diameter) vary by design, but the average is approximately $74.

For DL3, a 500kVA single-phase unit, the high-voltage connector is a single, wet-process porcelain bushing, 25 kV, 125 BIL, costing $6. The low-voltage bushings are two four-hole “J” Spade 500kVA, 277V, costing $60 for the set. The internal hardware includes a core clamp ($30), nameplate ($0.65), and miscellaneous hardware ($20), totaling $50.65. The design software optimized the tank cost with each design, including radiators (external cooling) for this kVA rating. The resultant finished round tank has a diameter of 33" to 52", with an average cost of approximately $627 (including radiators).

For DL4, a 150kVA three-phase, pad-mounted unit, the high-voltage bushings are three externally clamped, universal high-voltage bushing wells, 8.3/14.4 kV, 95 BIL, costing $7 each. The low-voltage bushings are three copper studs at $8 each. The internal hardware includes core clamps ($30), nameplate ($0.65), and miscellaneous hardware ($45), totaling $75.65. The optimized finished tank sizes measure 50 inches high and vary in width and depth. The finished rectangular, welded tank has an average cost of approximately $382.

For DL5, a 1500kVA three-phase, pad-mounted unit, the high-voltage bushings are three externally clamped, universal high-voltage bushing wells, 15.2/26.3 kV, 125kV BIL, costing $20 each. The low-voltage bushings are four externally clamped bushings, each having six-hole spade, costing $160 for the set. The internal hardware includes core clamps ($60), nameplate ($0.65), and miscellaneous hardware ($45), totaling $105.65. The optimized finished tank sizes measure 70 inches high and vary in width and depth. The finished rectangular, welded tank, including radiators as specified by the design software, has an average cost of approximately $1,015.

Table 5.4.3 Summary Table of Fixed Material Costs for Liquid-Immersed Units

Item	DL1	DL2	DL3	DL4	DL5
High voltage bushings	$14	$6	$6	$21	$60
Low voltage bushings	$20	$8	$60	$24	$160
Core clamp, nameplate, and misc. hardware	$25.65	$19.15	$50.65	$75.65	$105.65
Transformer tank average cost*	~$141	~$74	~$627	~$382	~$1,015

* Transformer tank steel is used in the design optimization software and varies with the efficiency (and size) of each design. DL3 and DL5 include calculated costs of radiators, which are scaled for each design based on the required cooling surface area.

5.4.3 Material Inputs to the Design Software – Dry-Type

Table 5.4.4 presents the material prices for a typical dry-type transformer manufacturer over the five-year 2006-2010 time horizon, indicating the current (2010), minimum (2006), and maximum (2008) prices (all in constant 2010$) The highlighted columns are the prices DOE used in the engineering analysis.

Table 5.4.4 Manufacturer's Material Prices for Dry-Type Design Lines

Material	**Units**	**2010 Price** *2010$*	**2006 Price (Min.)** *2010$*	**2008 Price (Max.)** *2010$*	**2010** *2010$*	**2009** *2010$*	**2008** *2010$*	**2007** *2010$*	**2006** *2010$*
M12 core steel	*$/lb*	1.03	0.99	1.24	1.03	1.08	1.24	1.14	0.99
M6 core steel	*$/lb*	1.46	1.10	1.70	1.46	1.61	1.70	1.47	1.10
M5 core steel	*$/lb*	1.51	1.15	1.74	1.51	1.64	1.74	1.49	1.15
M4 core steel	*$/lb*	1.59	1.20	1.78	1.59	1.68	1.78	1.52	1.20
M3 core steel	*$/lb*	1.88	1.23	2.02	1.88	1.93	2.02	1.58	1.23
M2 core steel	*$/lb*	2.00	1.54	2.16	2.00	1.98	2.16	2.02	1.54
H-0 DR core steel (laser scribed)	*$/lb*	2.06	1.65	2.50	2.06	2.34	2.50	2.10	1.65
SA1 (amorphous) finished core, volume production	*$/lb*	2.38	0.00	2.82	2.38	2.26	2.82	0.00	0.00
Copper wire, rectangular 0.1 x 0.2, Nomex wrapped	*$/lb*	4.63	4.63	5.46	4.63	3.87	5.46	5.20	4.63
Aluminum wire, rectangular 0.1 x 0.2, Nomex wrapped	*$/lb*	2.19	1.43	1.62	2.19	1.53	1.62	1.49	1.43
Copper strip, thickness range 0.02-0.045	*$/lb*	4.25	3.87	4.17	4.25	3.08	4.17	4.31	3.87
Aluminum strip, thickness range 0.02-0.045	*$/lb*	1.57	1.72	1.87	1.57	1.51	1.87	1.86	1.72
Nomex insulation	*$/lb*	24.50	15.99	22.47	24.50	24.37	22.47	19.18	15.99
Cequin insulation	*$/lb*	5.53	4.48	4.71	5.53	5.04	4.71	4.76	4.48
Impregnation	*$/gal*	22.55	20.00	21.14	22.55	22.38	21.14	20.59	20.00
Winding combs	*$/lb*	12.34	7.08	11.93	12.34	12.51	11.93	11.11	7.08
Enclosure Steel	*$/lb*	0.38	0.38	0.47	0.38	0.38	0.47	0.40	0.38

On the following pages, all the material prices entered into the design software for dry-type distribution transformers are given. As shown in these tables, DOE marked up the material prices before being entering them into the design software.

Table 5.4.5 Marked-up Material Prices for Dry-Type Units, Current Year (2010) Price Scenario

Item and Description	Units	Current 2010 Price *2010$*	Scrap & Handling	Factory Overhead	Non-Production	Software Input
M12 core steel	$/lb	1.03	1.025	1.125	1.25	1.49
M6 core steel	$/lb	1.46	1.025	1.125	1.25	2.10
M5 core steel	$/lb	1.51	1.025	1.125	1.25	2.18
M4 core steel	$/lb	1.59	1.025	1.125	1.25	2.28
M3 core steel	$/lb	1.88	1.025	1.125	1.25	2.70
M2 core steel	$/lb	2.00	1.025	1.125	1.25	2.88
H-0 DR core steel (laser scribed)	$/lb	2.06	1.025	1.125	1.25	2.97
SA1 (amorphous) finished core, volume production	$/lb	2.38	1.015	1.125	1.25	3.40
Copper wire, rectangular 0.1 x 0.2, Nomex wrapped	$/lb	4.63	1.025	1.125	1.25	6.67
Aluminum wire, rectangular 0.1 x 0.2, Nomex wrapped	$/lb	2.19	1.025	1.125	1.25	3.15
Copper strip, thickness range 0.02-0.045	$/lb	4.25	1.025	1.125	1.25	6.13
Aluminum strip, thickness range 0.02-0.045	$/lb	1.57	1.025	1.125	1.25	2.26
Nomex insulation	$/lb	24.50	1.025	1.125	1.25	35.31
Cequin insulation	$/lb	5.53	1.025	1.125	1.25	7.97
Impregnation	$/gal	22.55	-	1.125	1.25	31.71
Winding combs	$/lb	12.34	1.025	1.125	1.25	17.79
Enclosure Steel	$/lb	0.38	1.025	1.125	1.25	0.55

As stated in section 5.3, the OPS software does not take into account retooling costs associated with changing production designs. Therefore, to partially capture these differential costs in the design lines that had both buttlap and mitered designs, DOE used adders in DL7 and DL8. The adders specified an extra 10 cents per pound of core steel for full-mitered designs. More detailed costing of the retooling costs for mitering equipment will be covered in the manufacturer impact analysis (MIA) during the next phase of the rulemaking (see Chapter 12).

Similar to the liquid-immersed designs, there are fixed (and some partially variable) hardware costs associated with dry-type distribution transformers. These are discussed individually and then summarized in Table 5.4.6.

For DL6, a 25 kVA single-phase, low-voltage, dry-type transformer, the low-voltage and high-voltage terminal set costs $4. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs approximately $9.25. The fiberglass dog-bone duct-spacers used for this design line cost $0.24 per foot. DOE estimated the miscellaneous hardware costs at

$4.50. The ventilated enclosure – a 14-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 25kVA unit, and costs approximately $65.

For DL7, a 75 kVA three-phase, low-voltage, dry-type transformer, the fixed hardware costs are $9 for the high-voltage terminal board with connection points. DOE estimated the secondary (low-voltage) bus-bar to be seven feet at $1.50 per foot, or $10.50. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs approximately $19. The fiberglass dog-bone duct-spacers used for this design line cost $0.32 per foot. DOE estimated the miscellaneous hardware costs at $7. The ventilated enclosure – a 14-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 75kVA unit, and costs approximately $135.

For DL8, a 300 kVA three-phase, low-voltage, dry-type transformer, the high-voltage terminal board costs $27. DOE estimated the secondary (low-voltage) bus-bar to be nine feet at $2.50 per foot, or $22.50. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs approximately $36. The fiberglass dog-bone duct-spacers used for this design line cost $0.42 per foot. DOE estimated the miscellaneous hardware costs at $12. The ventilated enclosure – a 14-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 300kVA unit, and costs approximately $175.

For DL9, a 300 kVA three-phase, medium-voltage, dry-type transformer at 45 kV BIL, the low-voltage and high-voltage terminal set costs $75. DOE estimated the secondary (low-voltage) bus-bar to be eight feet at $10 per foot, or $80. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs approximately $36. The fiberglass dog-bone duct-spacers used for this design line cost $0.42 per foot. DOE estimated the miscellaneous hardware costs at $25. The ventilated enclosure – a 14-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 300 kVA unit, and costs approximately $240.

For DL10, a 1500 kVA three-phase, medium-voltage, dry-type transformer at 45 kV BIL, the low-voltage and high-voltage terminal set costs $120. DOE estimated the low-voltage bus-bar to be 14 feet at $10 per foot, or $140. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs approximately $120. DOE accounted for the cost of additional bracing in the amorphous design since the amorphous design uses a wound core rather than a round, cruciform core like the other designs. This extra bracing is needed for the amorphous design due to the size of DL10 (1500 kVA). The weight of the added bracing was calculated as 7 percent of the core and coil weight, and was multiplied by the price for enclosure steel to derive a cost. The bracing weighs 600 pounds on average and costs approximately $230. The fiberglass dog-bone duct-spacers used for this design line cost $0.52 per foot. DOE estimated the miscellaneous hardware costs at $42. The ventilated enclosure – a 12-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 1500 kVA unit, and costs approximately $740.

For DL11, a 300 kVA three-phase, medium-voltage, dry-type at 95 kV BIL, the low-voltage and high-voltage terminal set costs $100. The high-voltage terminal boards cost $27. DOE estimated the low-voltage bus-bar is estimated to be 10 feet at $8 per foot, or $80. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $42. The fiberglass dog-bone duct-spacers used for this design line cost $0.42 per foot. DOE estimated the miscellaneous hardware costs at $32. The ventilated enclosure – a 14-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 300 kVA unit, and costs approximately $400.

For DL12, a 1500 kVA three-phase, medium-voltage, dry-type at 95 kV BIL, the low-voltage and high-voltage terminal set costs $135. The high-voltage terminal boards cost $27. DOE estimated the low-voltage bus-bar is estimated to be 16 feet at $12 per foot, or $192. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $125. DOE accounted for the cost of additional bracing in the amorphous design since the amorphous design uses a wound core rather than a round, cruciform core like the other designs. This extra bracing is needed for the amorphous design due to the size of DL12 (1500 kVA). The weight of the added bracing was calculated as 7 percent of the core and coil weight, and was multiplied by the price for enclosure steel to derive a cost. The added bracing weighs 700 pounds on average and costs approximately $270. The fiberglass dog-bone duct-spacers used for this design line cost $0.56 per foot. DOE estimated the miscellaneous hardware costs at $54. The ventilated enclosure – a 12-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 1500 kVA unit, and costs approximately $810.

For DL13, a 2000 kVA three-phase, medium-voltage, dry-type at 125 kV BIL, the low-voltage and high-voltage terminal set costs $150. The high-voltage terminal boards cost $27. DOE estimated the low-voltage bus-bar is estimated to be 18 feet at $15 per foot, or $270. The mounting frame that attaches the core/coil assembly to the transformer enclosure costs $175. DOE accounted for the cost of additional bracing in the amorphous design since the amorphous design uses a wound core rather than a round, cruciform core like the other designs. This extra bracing is needed for the amorphous design due to the size of DL13 (2000 kVA). The weight of the added bracing was calculated as 7 percent of the core and coil weight, and was multiplied by the price for enclosure steel to derive a cost. The added bracing weighs 850 pounds on average and costs approximately $330. The fiberglass dog-bone duct-spacers used for this design line cost $0.60 per foot. DOE estimated the miscellaneous hardware costs at $60. The ventilated enclosure – a 12-gauge steel enclosure, base, and mounting feet – varies with the size of the core-coil assembly for the 2000 kVA unit, and costs approximately $900.

Table 5.4.6 Summary Table of Fixed Material Costs for Dry-Type Units

Item	DL6	DL7	DL8	DL9	DL10	DL11	DL12	DL13
LV and HV terminals (set)	$4	n/a	n/a	$75	$120	$100	$135	$150
HV terminal board(s)	n/a	$27	$27	$27	$27	$27	$27	$27
LV bus-bar	n/a	$10.50	$22.50	$80	$140	$80	$192	$270
Core/coil mounting frame	$9.25	$19	$36	$36	$120	$42	$125	$175
Additional Bracing	n/a	n/a	n/a	n/a	~$230	n/a	~$270	~$330
Nameplate	$0.65	$0.65	$0.65	$0.65	$0.65	$0.65	$0.65	$0.65
Dog-bone duct spacer (ft.)	$0.24	$0.32	$0.42	$0.42	$0.52	$0.42	$0.56	$0.60
Winding combs (lb.)	n/a	n/a	n/a	n/a	n/a	$10.00	$10.00	$10.00
Misc. hardware	$4.50	$7	$12	$25	$42	$32	$54	$60
Enclosure (12, 14 gauge)	~$65	~$135	~$175	~$240	~$740	~$400	~$810	~$900

LV = low voltage
HV = high voltage

5.4.4 Labor Costs

Labor costs are a critical aspect of the cost of manufacturing a distribution transformer. DOE used the same hourly labor cost for both liquid and dry-type distribution transformers. It developed the hourly cost of labor using a similar approach to the development of the cost of materials; however, it used different markups. DOE developed the markups shown in Table 5.4.7 after reviewing publicly available information, speaking with transformer manufacturers during 2010, and consulting with industry experts familiar with transformer manufacturing in the U.S.

Table 5.4.7 Labor Markups for Liquid-Immersed and Dry-Type Manufacturers

Item description	Markup percentage	Rate per hour
Labor cost per hour*		$ 16.80
Indirect Production**	33%	$ 22.35
Overhead***	30%	$ 29.05
Fringe†	24%	$ 36.03
Assembly Labor Up-time††	43%	$ 51.52
Fully-Burdened Cost of Labor		**$ 51.52**

* Cost per hour is from U.S. Census Bureau, *2007 Economic Census - Detailed Statistics*, published October 2009. Data for NAICS code 3353111 "Power and distribution transformers, except parts" Production workers hours and wages.
** Indirect production labor (e.g., production managers, quality control) as a percent of direct labor on a cost basis. Navigant Consulting, Inc. (NCI) estimate.
*** Overhead includes commissions, dismissal pay, bonuses, vacation, sick leave, and social security contributions. NCI estimate.
† Fringe includes pension contributions, group insurance premiums, workers compensation. Source: U.S. Census Bureau, *2007 Economic Census - Detailed Statistics*, published October 2009. Data for NAICS code 3353111 "Power and distribution transformers, except parts" Total fringe benefits as a percent of total compensation for all employees (not just production workers).
†† Assembly labor up-time is a factor applied to account for the time that workers are not assembling units and/or reworking unsatisfactory units. The markup of 43 percent represents a 70 percent utilization (multiplying by 100/70). NCI estimate.

There is several labor steps involved in manufacturing a liquid-immersed transformer. DOE prepared estimates of the amount of labor involved, some varying with the transformer design and others fixed on a per-unit basis. These steps are described below, and the amount of time dedicated to each is given in Table 5.4.8.

- Cutting, Forming, and Annealing – This task involves cutting the core steel to lengths on a distributed-gap core cutting machine, forming the resulting "donut" of core steel into a rectangular shape in a hydraulic press, and then annealing the core in a high temperature annealing furnace. DOE calculated the labor involved in these activities based on the weight of core (pounds) multiplied by a constant, which varies with the lamination thickness of the core steel. For DL1, DL2, and DL4, on M6 designs the constant is 0.08, M5 is 0.09, M4 is 0.10, M3 (with or without Lite Carlite) and ZDMH are 0.125, and M2 (with or without Lite Carlite) is 0.16. For DL3 and DL5, on M6 designs the constant is 0.05, M5 is 0.06, M4 is 0.07, M3 (with or without Lite Carlite) and ZDMH are 0.09, and M2 (with or without Lite Carlite) is 0.11. For the prefabricated core — SA1 (amorphous material)—DOE set the labor for cutting, forming, and annealing to zero.

- Primary Winding – This task entails winding the primary conductor of the transformer. It includes set-up time as well as winding time. The labor hours vary with the number of turns (per phase) for the primary winding. For DL1, DL2, and DL4, the winding time is 0.0001 hours per turn. For these smaller kVA ratings (and smaller cores), this rate is very low because some of the larger, liquid-immersed manufacturers wind multiple coils simultaneously on the same winding machine. This manufacturing approach improves throughput and productivity at the facility. The rate of 0.0001 hours per turn equates to approximately one-third of a second per turn. On DL3 and DL5, due to the larger coil size associated with these units, the winding time is 0.002 hours per turn (approximately 7.2 seconds per turn).

- Secondary Winding – This task involves winding the secondary conductor of the transformer. It includes set-up time as well as winding time. On a distribution (step-down) transformer, the number of secondary turns is always less than the primary. For the liquid-immersed units, which are taking a relatively high primary voltage and dropping to below 600V, the turns ratio can be as large as 100:1. For this reason, the hours per turn of the secondary are considerably higher than the primary, because there are fewer turns over which to amortize the set-up time as well as a slower winding rate for the secondary, which has larger cross-sectional area than the primary. For DL1, DL2, and DL4, the hours per turn of the secondary are 0.015 (54 seconds per turn); for DL3 and DL5, the hours per turn are 0.02 (72 seconds per turn).

- Lead Dressing – Once a wound coil is taken off the winding machine, work must be performed on the leads to prepare them for the next manufacturing step. Enamel is removed to enable good electrical connection and insulating tubing is slipped over the cable. This is a fixed amount of labor, and does not vary with efficiency or design. The estimated times are 0.5 hours for DL1 and DL4, 0.07 hours for DL2, 0.35 hours for DL3, and 1.0 hour for DL5.

- Coil Varnishing and Baking – Once they are complete, the coils are vacuum-dipped in varnish and baked in an oven to cure the varnish and enhance the integrity of the coil. This task varies slightly with kVA rating, but does not vary with efficiency. The estimated times are 0.10 hours for DL1, 0.07 hours for DL2, 0.15 hours for DL3, 0.17 hours for DL4, and 0.25 hours for DL5.

- Core Assembly ("Lacing") – This task involves assembling and banding the annealed wound core laminations around varnished windings. The annealed bundle of core steel is disassembled from the inside out by grabbing approximately 1/4 inch bundles, then reassembling the core steel around the coils. Once all the laminations are reassembled, the core material is clamped to maintain the structure. The activity involves feeding a banding strip around the core material and using a locking clamp to compress and contain the core material. The labor rate varies with stack height and lamination thickness for each design. The time for core assembly is approximately 0.5 hours for DL1, 0.3 hours for DL2, 1.5 hours for DL3, 1 hour for DL4, and 3.5 hours for DL5.

- Tanking and Impregnating – This task involves inserting and fastening the core/coil assembly into the tank. Then, a vacuum is pulled and oil is introduced to the tank. On round tanks, the vacuum and oil step is done through a lid attached to the top of the unit. On the rectangular and pad-mounted tanks, the vacuum is pulled in a chamber, which takes a little longer per unit. Finally, tap changers and bushings are mounted, and bolted connections made. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating and tank shape. The estimates of labor time for the five liquid-immersed design lines are: 0.5 hours for DL1, 0.11 hours for DL2, 0.5 hours for DL3, 0.62 hours for DL4, and 1.7 hours for DL5.

- Inspection – This activity involves verifying that the transformer is assembled properly and is up to a manufacturer's quality specification. This task includes inspecting the lead dressing, lead tie-up, and other quality certification specifications. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time are 0.10 hours for DL1 and DL3, 0.05 hours for DL2, 0.15 hours for DL4, and 0.20 hours for DL5.

- Preliminary Test This step involves conducting a test to ensure that the core/coil meets the specified turns ratio, polarity, core loss, etc. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time are 0.10 hours for DL1, DL3, and DL4; 0.03 hours for DL2; and 0.15 hours for DL5.

- Final Test – This activity involves testing of the final, assembled unit, with the core/coil assembly immersed in oil. This test verifies that the unit meets the guaranteed values, including core and coil losses, impedance, and dielectric tests. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time are 0.15 hours for DL1 and DL3, 0.07 hours for DL2, 0.20 hours for DL4, and 0.25 hours for DL5.

- Pallet Loading – This activity involves preparing the transformer for shipping to the customer. This includes loading the finished transformer onto a pallet, banding the transformer to the pallet, wrapping, and all other necessary steps for shipping. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time are 0.27 hours for DL1, 0.06 hours for DL2, 0.75 hours for DL3, 0.50 hours for DL4, and 3 hours for DL5.

- Marking and Miscellaneous – This task involves preparing any extra markings around the bushings or on the surface of the transformer and other miscellaneous labor associated with preparing the finished transformer for the customer. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time are 0.28 hours for DL1, 0.07 hours for DL2, 0.35 hours for DL3, 0.31 hours for DL4, and 0.75 hours for DL5.

Table 5.4.8 summarizes the estimates of labor time that DOE used for the five liquid-immersed units.

Table 5.4.8 Summary of Labor Times for Liquid-Immersed Units

Labor Activity	**DL1** ***hrs.***	**DL2** ***hrs.***	**DL3** ***hrs.***	**DL4** ***hrs.***	**DL5** ***hrs.***
Cutting, Forming, & Annealing	~1.00	~0.75	~4.00	~3.00	~8.50
Primary Winding (hrs/turn)	0.0001	0.0001	0.002	0.0001	0.002
Secondary Winding (hrs/turn)	0.015	0.015	0.020	0.015	0.020
Lead Dressing	0.50	0.07	0.35	0.50	1.00
Baking Coils	0.10	0.07	0.15	0.17	0.25
Core Assembly	~0.50	~0.30	~1.50	~1.00	~3.50
Tanking and Impregnating	0.50	0.11	0.50	0.62	1.70
Inspection	0.10	0.05	0.10	0.15	0.20
Preliminary Test	0.10	0.03	0.10	0.10	0.15
Final Test	0.15	0.07	0.15	0.20	0.25
Pallet Loading	0.27	0.06	0.75	0.50	3.00
Marking and Misc.	0.28	0.07	0.35	0.31	0.75

Likewise, there is several labor steps involved in manufacturing a dry-type transformer. DOE prepared estimates of the amount of labor involved, some varying with the transformer design and others fixed on a per-unit basis. These steps are described below, and the amounts of time dedicated to each are summarized in Table 5.4.9.

- Core Stacking – This task involves stacking (assembling) the cut steel laminations into a distribution transformer core. The amount of labor for this task varies by kVA rating, stack height, and whether the core is grain-oriented or non-oriented. Thus, the labor for core stacking varies with the efficiency of the transformer. Approximate labor hours for core stacking vary from as short as 0.25 hours/inch for a 25 kVA single-phase, low-voltage unit to 0.9 hours/inch for a 2000 kVA, 125kV BIL three-phase, medium-voltage unit. For the prefabricated core – SA1 (Amorphous material) – the labor for core stacking (i.e., cutting, forming, and annealing) is set to zero.

- Primary Winding – This task encompasses winding the primary conductor of the transformer. It includes set-up time as well as winding time. The labor hours vary with the number of turns (per phase) for the primary winding. For DL6, the winding time is the quickest, with 0.001 hours/turn. DL7 is slightly longer with 0.0015 hours/turn. DL8 has a winding time of 0.01 hours/turn. For DL9, the winding time is 0.008 hours/turn. For DL10, the winding time is 0.0225 hours/turn. DL11 has a winding time of 0.005 hours/turn. DL 12 and DL13 have the same winding time—0.0125 hours/turn.

- Secondary Winding – This task involves winding the secondary conductor of the transformer. It includes set-up time as well as winding time. The hours per turn of the secondary are considerably higher than the primary, because there are fewer turns over which to amortize the set-up time as well as a slower winding rate for the secondary, which has larger cross sectional area. The hours per turn vary from 0.01 to 0.125, depending on the kVA rating (design line).

- Lead Dressing – Once a wound coil is taken off the winding machine, work must be performed on the leads to prepare them for the next manufacturing step. Enamel is removed to enable good electrical connection and insulating tubing is slipped over the cable. For a given kVA rating, this is a fixed amount of labor, and does not vary with efficiency or design. The range is from 0.15 to 1.0 hours per unit.

- Assembly – This task involves installing the wound coils onto the partially assembled core, and then lacing the top (yoke) laminations to complete the core. It also includes setting all the core clamps and completing the core/coil assembly. DOE assumed the assembly time varies by kVA rating, but does not vary by design within a kVA rating. For example, DOE estimated the assembly time for a 1500kVA three-phase unit at six hours, while DOE estimated the assembly time for a 75kVA three-phase unit at one hour. The only exception is for amorphous designs in dry-type design lines that are 1500 kVA or greater. For DL 10, DL 12, and DL 13, DOE used an estimate of sixteen hours for assembly time to account for the added complexity of using an amorphous core in these large designs. This time estimate is based on time estimates for unpacking (2 hours), unlacing joints (1.5 hours), mounting cores in place (2 hours), re-lacing core joints (4 hours), setting cores in place (1.5 hours), and attaching the framing and bolting (5 hours).

- Inspection – This activity involves verifying that the transformer is assembled properly and is up to a manufacturer's quality specification. It includes inspecting the lead dressing, lead tie up, and other quality certification specifications. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The time estimates vary from 0.05 hours (three minutes) for the smaller kVA ratings to 0.25 hours (15 minutes) for the larger units.

- Preliminary Test – This step involves conducting a test to ensure that the core/coil meets the specified turns ratio, polarity, core loss, etc.   The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The estimates of labor time range from 0.05 hours (three minutes) for the smaller kVA ratings to 0.5 hours (30 minutes) for the larger units.

- Final Test – This activity involves testing the final, assembled unit, with the core/coil assembly immersed in oil. This test verifies that the unit meets the guaranteed values, including core and coil losses, impedance, and dielectric tests. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. Similar to the preliminary test, the labor time estimates range from 0.1 hours (six minutes) for the smaller kVA ratings to 0.75 hours (45 minutes) for the larger units.

- Enclosure Manufacturing – The labor estimate for this task encompasses all activity associated with the cutting, forming, assembly, priming, painting, and preparation of the enclosure. This labor estimate varies with the kVA rating, spanning from 0.75 hours for the 25kVA single-phase unit up to eight hours for the 1500 and 2000kVA cabinets.

- Packing – This activity involves preparing the transformer for shipping to the customer. This includes loading the finished transformer onto a pallet, banding the transformer to the pallet, wrapping, and all other necessary steps for shipping. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The time estimate ranges from 0.20 hours at the low end to 2.0 hours at the higher kVA ratings.

- Marking and Miscellaneous – This task involves preparing any extra markings on the terminal board or on the surface of the transformer, and other miscellaneous labor associated with preparing the finished transformer for the customer. The time for this activity does not vary with design or efficiency, but it does vary by kVA rating. The labor estimate ranges from 0.20 hours at the low end to 2.2 hours at the higher kVA ratings.

Table 5.4.9 presents the hours of labor needed to complete each step in the manufacturing process for all design lines containing dry-type transformers.

Table 5.4.9 Summary of Labor Times for Dry-Type Units

Labor Activity	DL6 *hrs.*	DL7 *hrs.*	DL8 *hrs.*	DL9 *hrs.*	DL10 *hrs.*	DL11 *hrs.*	DL12 *hrs.*	DL13 *hrs.*
Core Stacking (hrs/inch)	0.25	0.25 – 0.35	0.38	0.55	0.70	0.70	0.80	0.90
Primary Winding (hrs/turn)	0.001	0.0015	0.01	0.008	0.0225	0.005	0.0125	0.0125
Secondary Winding (hrs/turn)	0.01	0.011	0.040	0.035	0.125	0.035	0.075	0.100
Lead Dressing	0.15	0.25	0.50	0.60	1.00	0.60	1.00	1.00
Assembly, [Amorphous designs]	0.35	1.00	2.50	3.00	6.00, [16.00]	4.00	6.00, [16.00]	6.00, [16.00]
Inspection	0.05	0.05	0.10	0.10	0.25	0.10	0.25	0.25
Preliminary Test	0.05	0.05	0.10	0.10	0.50	0.15	0.50	0.50
Final Test	0.10	0.10	0.15	0.15	0.75	0.25	0.75	0.75
Enclosure Manufacturing	0.75	1.50	3.00	5.00	8.00	5.00	8.00	8.00
Packing	0.20	0.20	1.00	1.00	2.00	1.00	2.00	2.00
Marking and Miscellaneous	0.20	0.20	0.60	0.70	2.20	0.85	2.20	2.20

5.5 BASELINE EFFICIENCY AND CANDIDATE STANDARD LEVELS

DOE analyzed designs over a range of efficiency values for each representative unit. Within the efficiency range, DOE developed designs that approximate a continuous function of efficiency. However, DOE analyzes the incremental impacts of increased efficiency by comparing discrete efficiency benchmarks to a constant baseline efficiency. The baseline efficiency evaluated for each representative unit is the existing standard level efficiency for distribution transformers established in DOE's previous rulemaking. The incrementally higher efficiency levels, termed "candidate standard levels" (CSLs), are meant to characterize the cost-efficiency relationship above the baseline. These CSLs are ultimately used by DOE if it decides to amend the existing energy conservation standards.

5.5.1 Criteria for Selecting Candidate Standard Levels

For the preliminary analysis, DOE considered several criteria when setting CSLs. First, DOE harmonized the efficiency values across single-phase transformers and the per-phase kVA equivalent three-phase transformers. For example, a 50 kVA single-phase transformer would have the same efficiency as a 150 kVA three-phase transformer. This approach is consistent with DOE's methodology from the previous rulemaking. As such, DOE selected equivalent CSLs for several of the representative units that have equivalent per-phase kVA ratings.

Second, DOE selected equally spaced CSLs by dividing the entire efficiency range into 5–7 evenly spaced increments. The number of increments depended on the size of the efficiency range. This allowed DOE to examine impacts based on an appropriate resolution of efficiency for each representative unit.

Finally, DOE adjusted the position of some of the equally spaced CSLs and examined additional CSLs. These minor adjustments to the equally spaced CSLs allowed DOE to consider important efficiency values based on the results of the software designs. For example, DOE adjusted some CSLs slightly up or down in efficiency to consider the maximum efficiency potential of non-amorphous design options. Other CSLs were added to consider important benchmark efficiencies, such as the NEMA Premium efficiency for low-voltage dry-type distribution transformers. Lastly, DOE considered additional CSLs to characterize the maximum-technologically feasible design for representative units where the harmonized per-phase efficiency value would have been unachievable for one of the representative units. DOE characterized a maximum-technologically feasible CSL for both standard core technology and symmetric core technology.

5.5.2 Candidate Standard Levels Selected

Table 5.5.1 presents the efficiency identified for each baseline and CSL in the engineering analysis. Table 5.5.2 presents the incremental MSP for each of the least-costly design options at each CSL.

Table 5.5.1 Summary of Baselines and Candidate Standard Levels for Distribution Transformer Representative Units

Design Line	Representative Unit	Base-line	CSL1	CSL2	CSL3	CSL4	CSL5	CSL6	CSL7	CSL8
		Eff. [%]	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*	*Eff. [%]*
1	50 kVA, 65°C, single-phase, 60Hz, 14400V primary, 240/120V secondary, rectangular tank	99.08	99.17	99.27	99.36	99.46	99.55	99.60	N/A	N/A
2	25 kVA, 65°C, single-phase, 60Hz, 14400V primary, 120/240V secondary, round tank	98.91	99.02	99.13	99.24	99.35	99.46	N/A	N/A	N/A
3	500 kVA, 65°C, single-phase, 60Hz, 14400V primary, 277V secondary	99.42	99.48	99.54	99.57	99.61	99.67	99.73	99.76	N/A
4	150 kVA, 65°C, three-phase, 60Hz, 12470Y/7200V primary, 208Y/120V secondary	99.08	99.17	99.27	99.36	99.46	99.55	99.60	99.65	N/A
5	1500 kVA, 65°C, three-phase, 60Hz, 24940GrdY/14400V primary, 480Y/277V secondary	99.42	99.48	99.54	99.57	99.61	99.67	99.73	99.75	N/A
6	25 kVA, 150°C, single-phase, 60Hz, 480V primary, 120/240V secondary, 10kV BIL	98.00	98.23	98.47	98.60	98.70	98.93	99.17	99.40	N/A
7	75 kVA, 150°C, three-phase, 60Hz, 480V primary, 208Y/120V secondary, 10kV BIL	98.00	98.23	98.47	98.60	98.70	98.93	99.17	99.40	99.48
8	300 kVA, 150°C, three-phase, 60Hz, 480V Delta primary, 208Y/120V secondary, 10kV BIL	98.60	98.80	99.02	99.19	99.41	99.59	99.63	N/A	N/A
9	300 kVA, 150°C, three-phase, 60Hz, 4160V Delta primary, 480Y/277V secondary, 45kV BIL	98.82	98.97	99.12	99.28	99.43	99.58	99.62	N/A	N/A
10	1500 kVA, 150°C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL	99.22	99.31	99.40	99.50	99.59	99.68	99.71	N/A	N/A
11	300 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL	98.67	98.84	99.00	99.17	99.33	99.50	99.55	N/A	N/A
12	1500 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL	99.12	99.21	99.30	99.39	99.48	99.57	99.66	99.69	N/A
13	2000 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 125kV BIL	99.15	99.25	99.35	99.46	99.56	99.66	99.69	N/A	N/A

Note: CSLs shaded orange represent the max-tech efficiency for symmetric core designs.

Table 5.5.2 Summary of Incremental Manufacturer Selling Prices Over the Baseline for Distribution Transformer Representative Units

Design Line	Representative Unit	Base-line	CSL1	CSL2	CSL3	CSL4	CSL5	CSL6	CSL7
		$	$	$	$	$	$	$	$
1	50 kVA, 65°C, single-phase, 60Hz, 14400V primary, 240/120V secondary, rectangular tank	-	234	501	578	854	1,406	2,109	N/A
2	25 kVA, 65°C, single-phase, 60Hz, 14400V primary, 120/240V secondary, round tank	-	235	416	605	751	1,312	N/A	N/A
3	500 kVA, 65°C, single-phase, 60Hz, 14400V primary, 277V secondary	-	675	2,386	2,246	3,005	4,544	7,140	11,922
4	150 kVA, 65°C, three-phase, 60Hz, 12470Y/7200V primary, 208Y/120V secondary	-	364	331	764	1,313	2,730	4,286	N/A
5	1500 kVA, 65°C, three-phase, 60Hz, 24940GrdY/14400V primary, 480Y/277V secondary	-	1,663	5,509	6,040	6,694	10,613	43,740	N/A
6	25 kVA, 150°C, single-phase, 60Hz, 480V primary, 120/240V secondary, 10kV BIL	-	(2)	146	264	303	452	591	1,219
7	75 kVA, 150°C, three-phase, 60Hz, 480V primary, 208Y/120V secondary, 10kV BIL	-	18	117	288	565	1,171	1,234	2,703
8	300 kVA, 150°C, three-phase, 60Hz, 480V Delta primary, 208Y/120V secondary, 10kV BIL	-	520	1,037	2,734	3,730	7,334	N/A	N/A
9	300 kVA, 150°C, three-phase, 60Hz, 4160V Delta primary, 480Y/277V secondary, 45kV BIL	-	828	2,780	4,189	5,443	9,715	N/A	N/A
10	1500 kVA, 150°C, three-phase, 60Hz, 4160V primary, 480Y/277V secondary, 45kV BIL	-	5,561	9,469	12,907	14,341	31,275	N/A	N/A
11	300 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL	-	460	2,079	3,861	5,617	10,715	N/A	N/A
12	1500 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 95kV BIL	-	2,567	5,170	11,072	12,556	19,192	33,255	N/A
13	2000 kVA, 150°C, three-phase, 60Hz, 12470V primary, 480Y/277V secondary, 125kV BIL	-	3,929	10,513	18,017	24,196	44,046	N/A	N/A

Note: Does not include symmetric core designs. Based on reference case traditional core designs only.

5.6 RESULTS OF THE ANALYSIS ON EACH DESIGN LINE

This section provides a visual representation of the results of the engineering analysis. The scatter plots in this section show the relationship between the manufacturer's selling price and efficiency for each of the 13 design lines. Each dot on the plots represents one unique design created by the software at a given manufacturer's selling price and efficiency level. The placement of each dot (and the uniqueness of each design) is dictated by the design option combinations (core steel and windings), core shape, A/B combination, and the variable design parameters generated by the design software.

5.6.1 Traditional Core Designs for the Reference Case

The designs in this section represent the traditional core designs that DOE analyzed in the life-cycle cost and national impact analyses. In addition to the results provided in this section, DOE prepared scatter plots depicting the engineering analysis results for the 13 representative units, including watts of core and coil loss and the weight by efficiency (see Appendix 5A).

Figure 5.6.1 presents a plot of the manufacturer selling prices and efficiency levels for the full database of designs for the representative unit from DL1, a 50kVA single-phase, liquid-immersed, pad-mounted distribution transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.08 percent is met by designs using M3 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.25 percent, and can reach efficiencies of 99.60 percent.

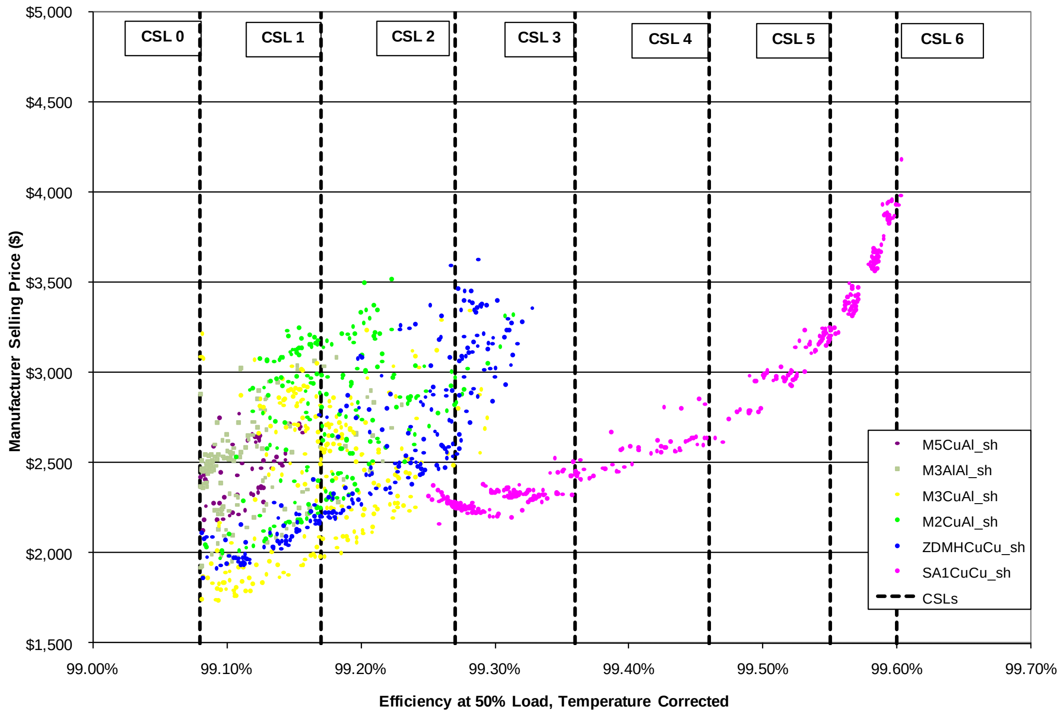

Figure 5.6.1 Engineering Analysis Results, Design Line 1

Figure 5.6.2 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL2, a 25kVA single-phase, liquid-immersed, pole-mounted distribution transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.91 percent is met by designs using M3 core steel or better, though it can be met with M4 or even M5 core steel designs.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.10 percent, and can reach efficiencies above 99.45 percent.

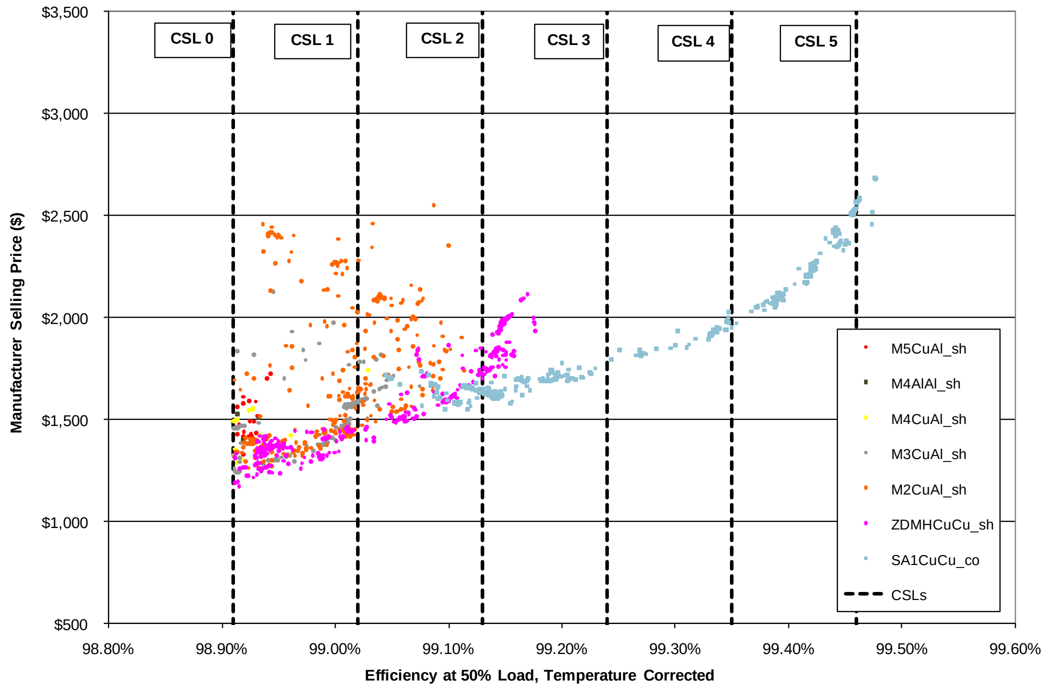

Figure 5.6.2 Engineering Analysis Results, Design Line 2

Figure 5.6.3 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL3, a 500kVA single-phase, liquid-immersed distribution transformer with radiators. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.42 percent is met by designs using M3 core steel or better, though it can be met with some M4 core steel designs.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.55 percent, and can reach efficiencies above 99.75 percent.

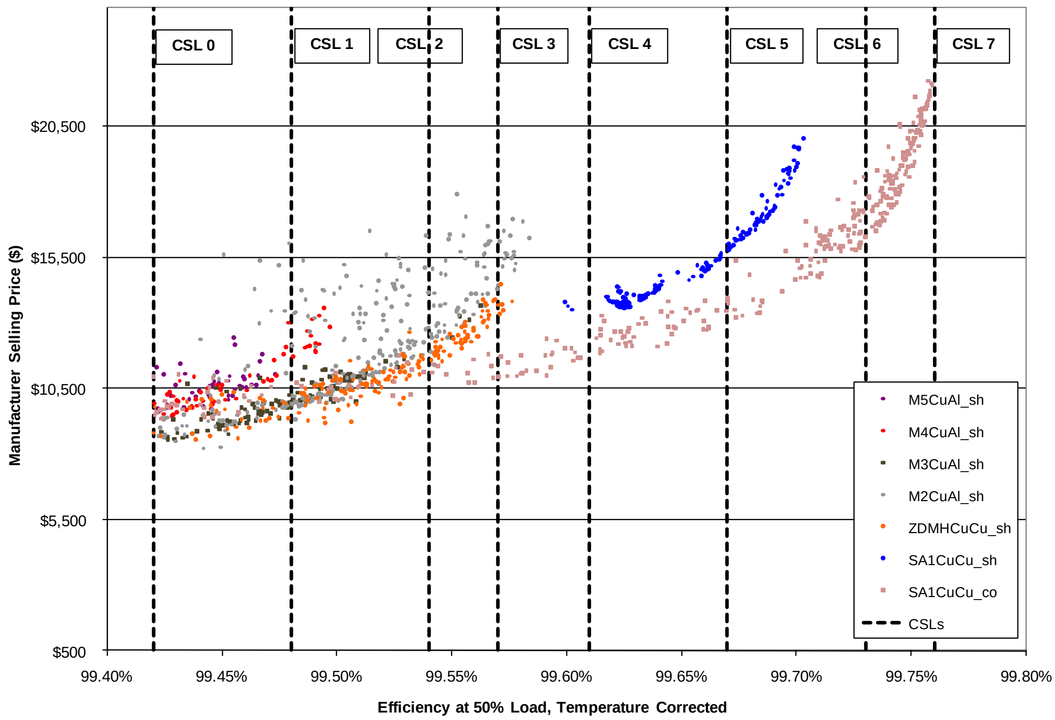

Figure 5.6.3 Engineering Analysis Results, Design Line 3

Figure 5.6.4 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL4, a 150kVA three-phase, liquid-immersed distribution transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.08 percent is met by designs using M3 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.18 percent, but amorphous designs have a minimum efficiency of 99.27 percent.
- The amorphous designs can reach efficiencies above 99.60 percent.

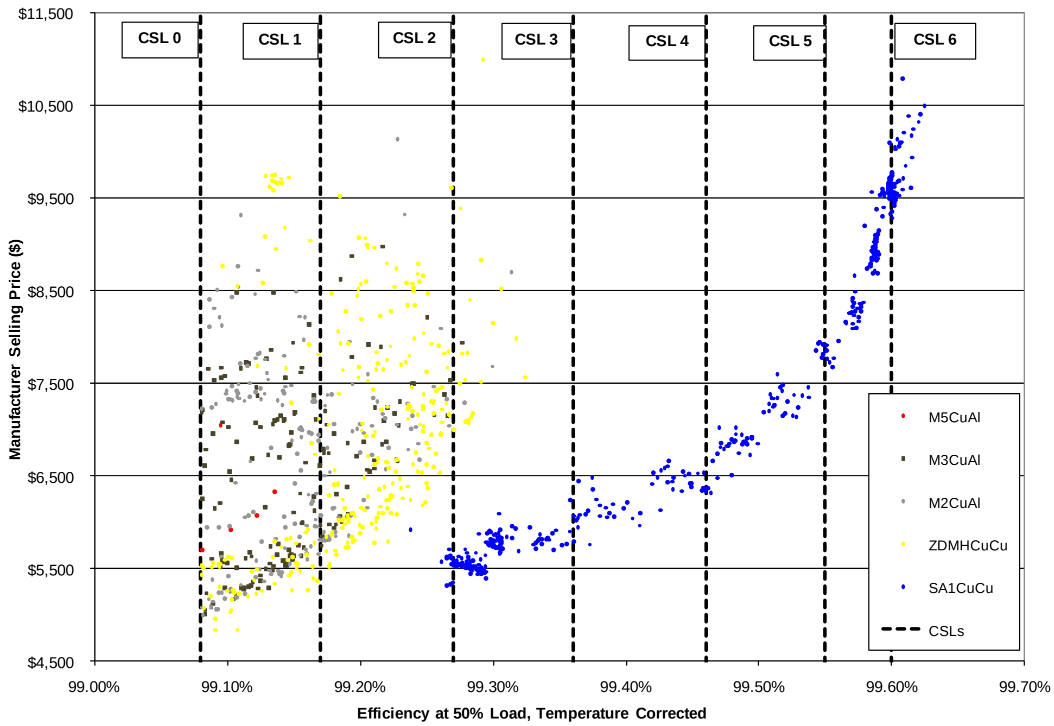

Figure 5.6.4 Engineering Analysis Results, Design Line 4

Figure 5.6.5 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL5, a 1500kVA three-phase, liquid-immersed distribution transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.42 percent is met by designs using M3 core steel or better, though it can be met with some M4 core steel designs.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.50 percent, and can reach efficiencies up to 99.74 percent.

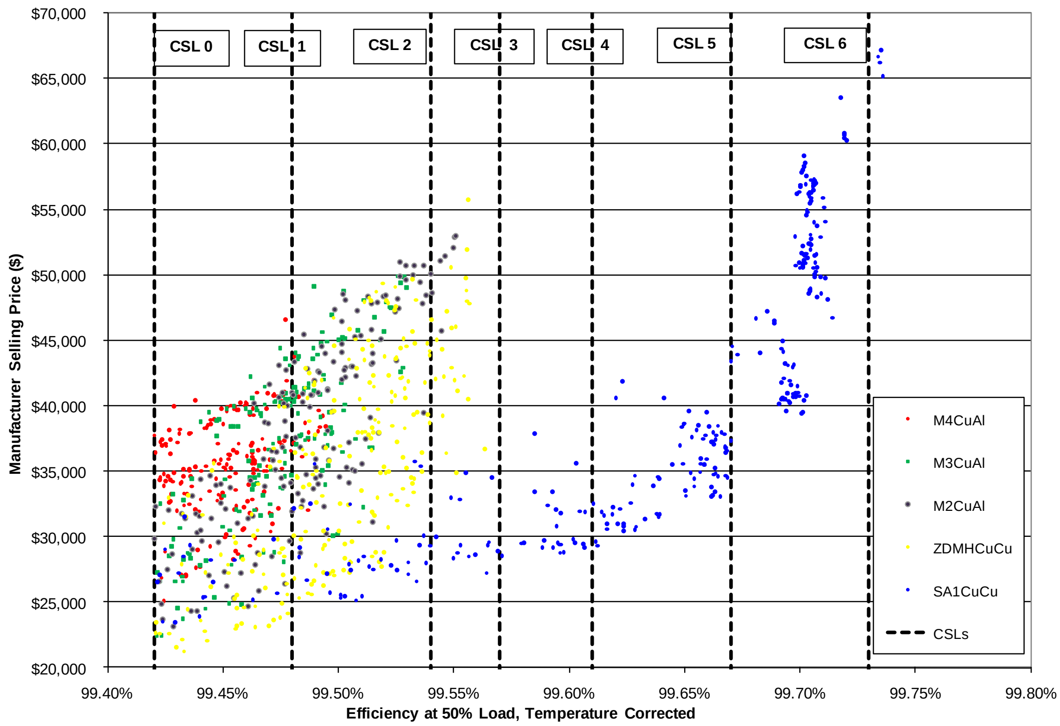

Figure 5.6.5 Engineering Analysis Results, Design Line 5

Figure 5.6.6 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL6, a 25kVA single-phase, low-voltage, dry-type distribution transformer. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.00 percent is met by designs using M6 core steel or better.
- The NEMA Premium efficiency level of 98.60 percent is met by designs using M4 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 98.70 percent, and can reach efficiencies above 99.40 percent.

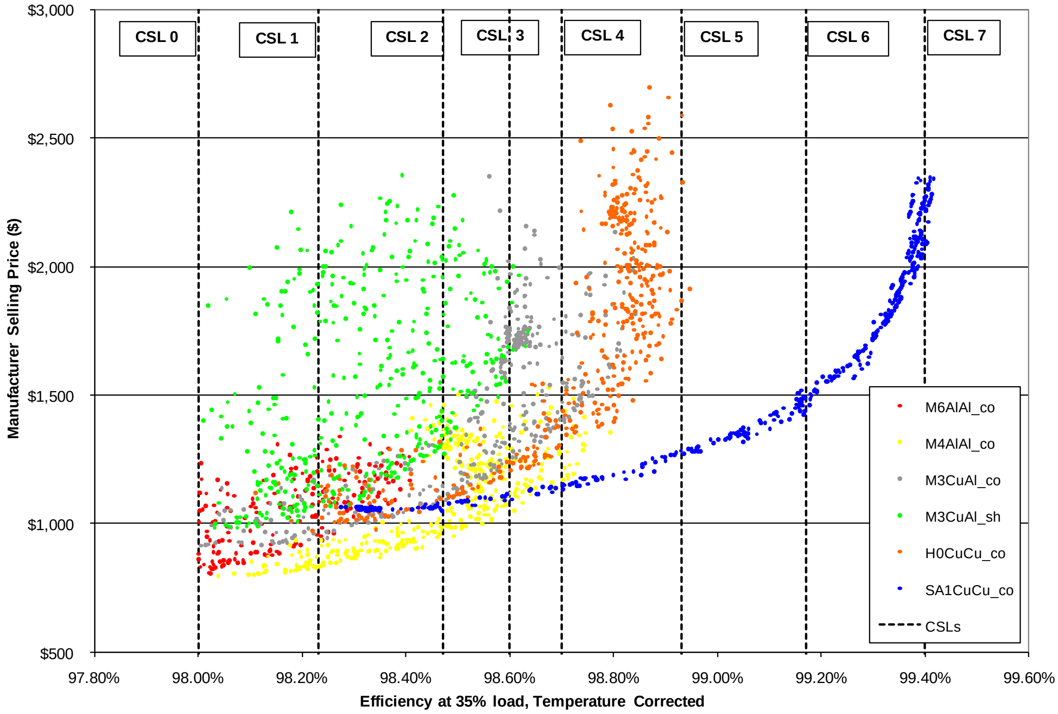

Figure 5.6.6 Engineering Analysis Results, Design Line 6

Figure 5.6.7 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL7, a 75kVA three-phase, low-voltage, dry-type distribution transformer. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.00 percent is met by designs using M12 core steel or better.
- The NEMA Premium efficiency level of 98.60 percent is met by designs using M6 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 98.95 percent, and can reach efficiencies above 99.40 percent.

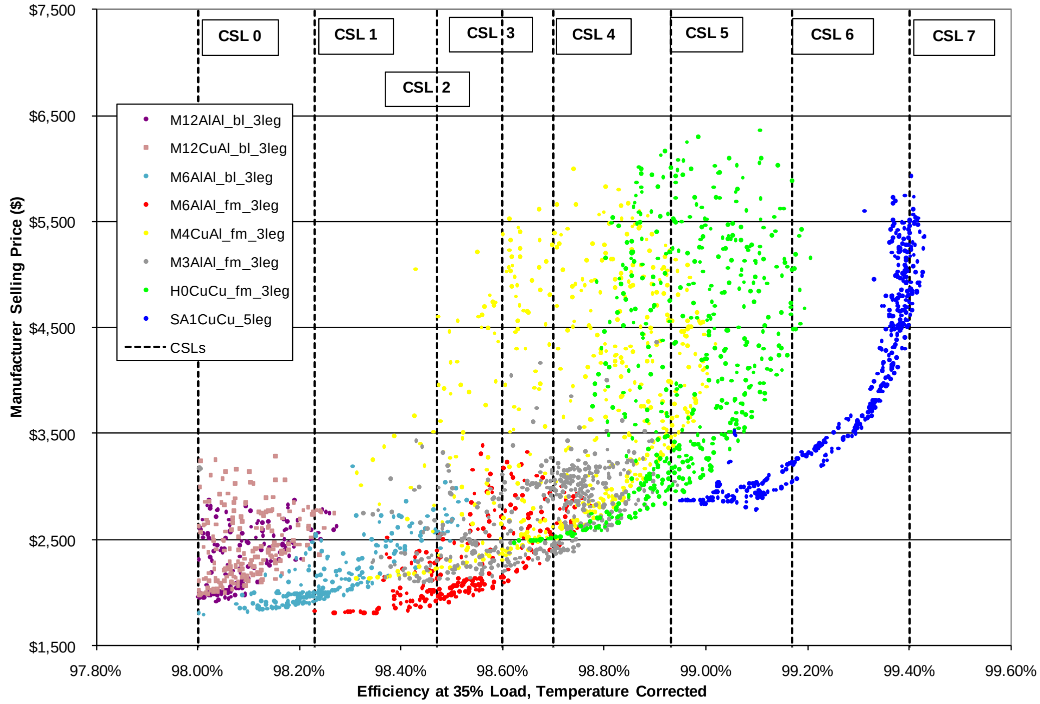

Figure 5.6.7 Engineering Analysis Results, Design Line 7

Figure 5.6.8 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL8, a 300kVA three-phase, low-voltage, dry-type distribution transformer. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.60 percent is met by designs using M6 core steel or better.
- The NEMA Premium efficiency level of 99.02 percent is met by designs using M3 core steel or better.
- The amorphous metal (SA1) core is the only design that can achieve an efficiency of 99.40 percent or greater, and can reach efficiencies up to 99.60 percent.

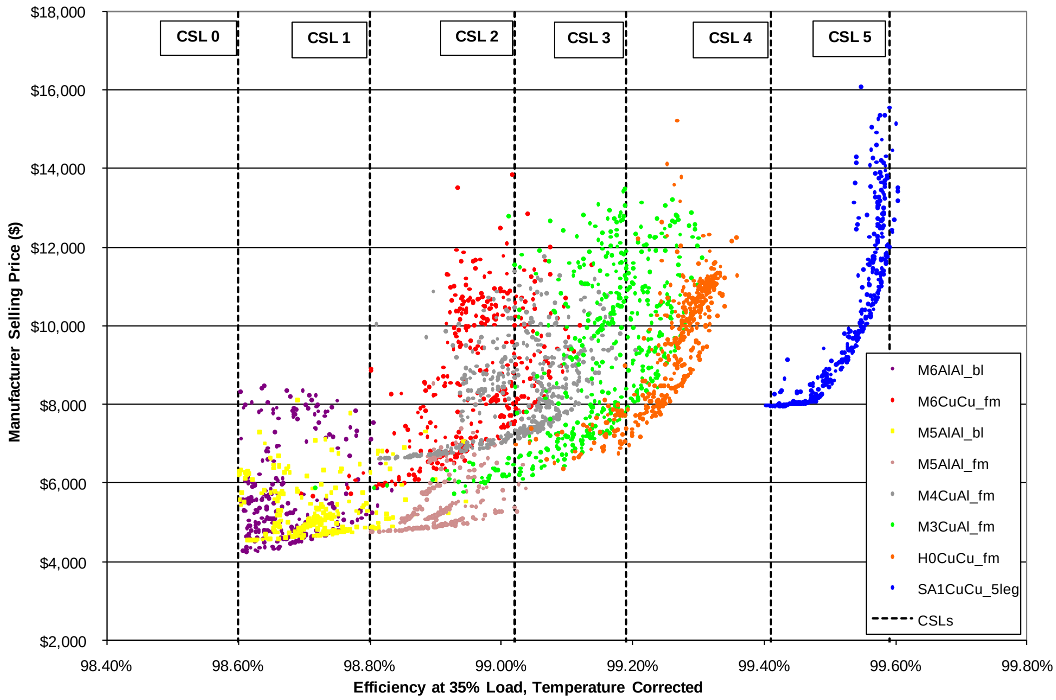

Figure 5.6.8 Engineering Analysis Results, Design Line 8

Figure 5.6.9 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL9, a 300kVA three-phase, medium-voltage, dry-type transformer with a 45kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.82 percent is met by designs using M6 core steel or better.
- The five-legged amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.20 percent, and can reach efficiencies up to 99.59 percent.

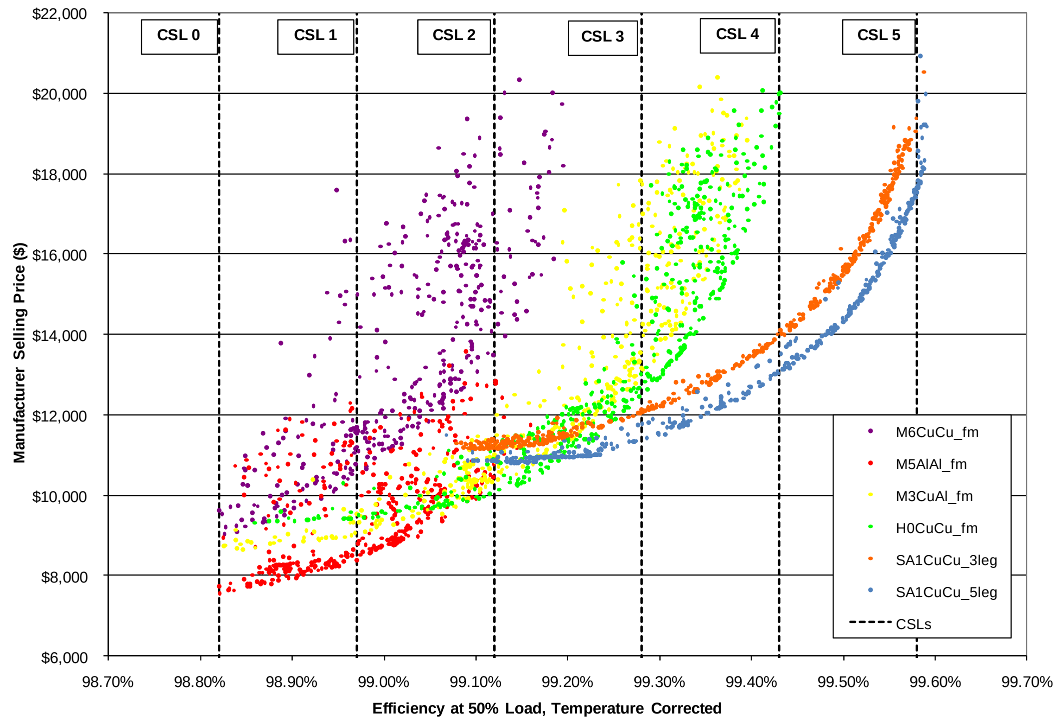

Figure 5.6.9 Engineering Analysis Results, Design Line 9

Figure 5.6.10 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL10, a 1500kVA three-phase, medium-voltage, dry-type transformer with a 45kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.22 percent is met by designs using M5 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.40 percent, and can reach efficiencies up to 99.70 percent.

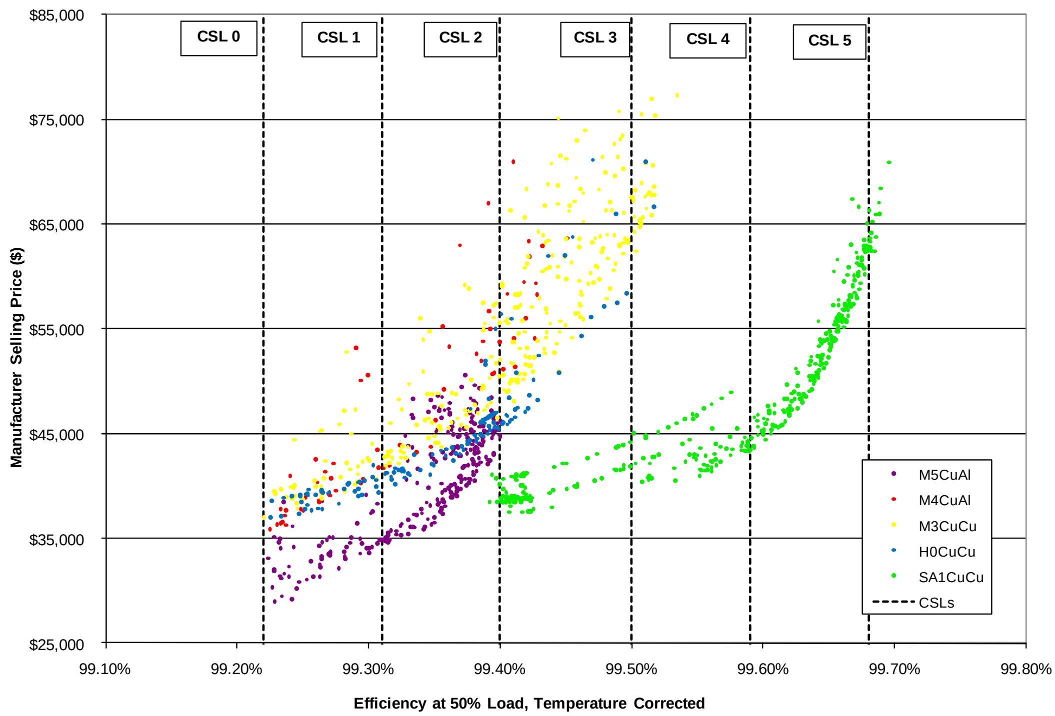

Figure 5.6.10 Engineering Analysis Results, Design Line 10

Figure 5.6.11 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL11, a 300kVA three-phase, medium-voltage, dry-type transformer with a 95kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load. The following observations can be made about this scatter plot:

- The current standard efficiency level of 98.67 percent is met by designs using M4 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.00 percent, and can reach efficiencies up to 99.50 percent.

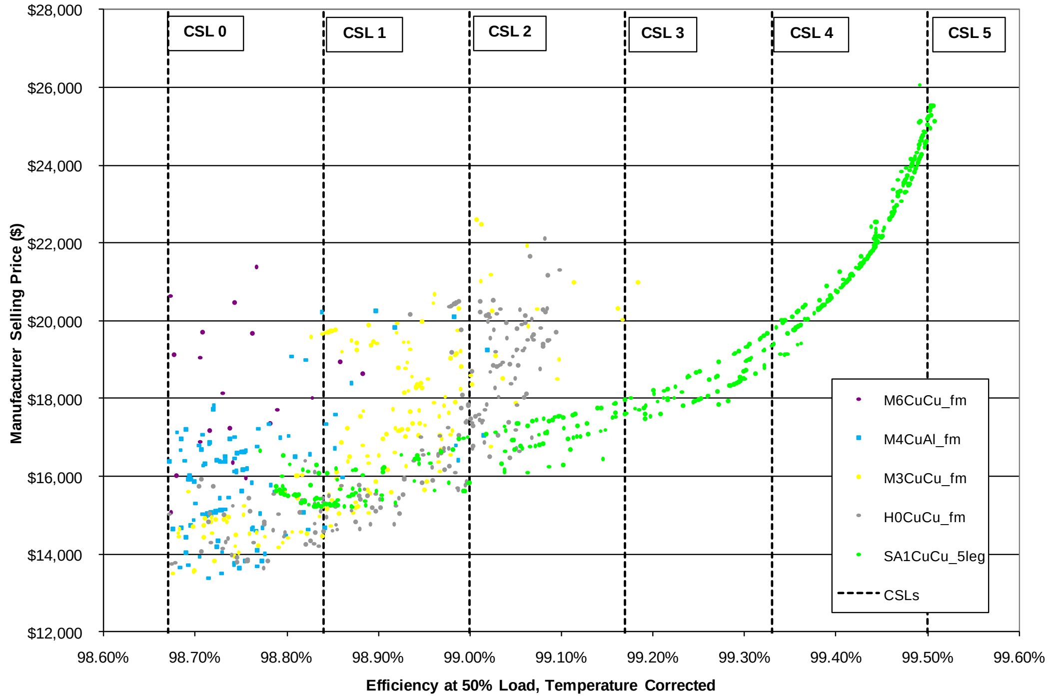

Figure 5.6.11 Engineering Analysis Results, Design Line 11

Figure 5.6.12 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL12, a 1500kVA three-phase, medium-voltage, dry-type transformer with a 95kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.12 percent is met by designs using M5 core steel or better.
- The amorphous metal (SA1) core is the most cost-effective design for any efficiency level above 99.40 percent, and can reach efficiencies above 99.65 percent.

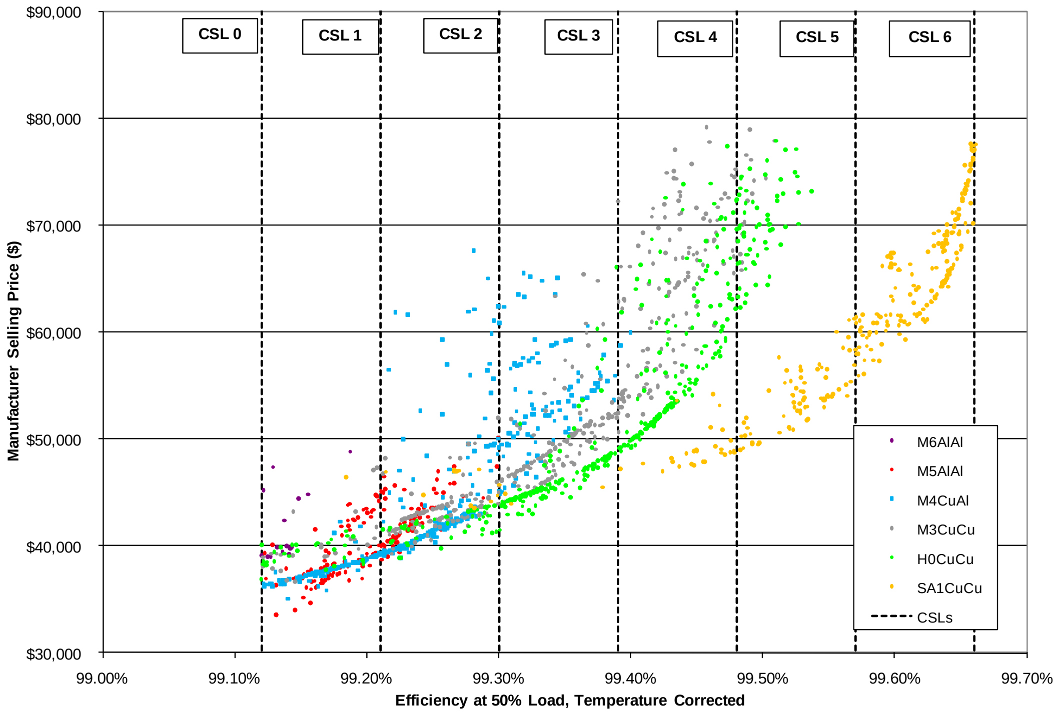

Figure 5.6.12 Engineering Analysis Results, Design Line 12

Figure 5.6.13 presents a plot of the manufacturer sales prices and efficiency levels for the full database of designs for the representative unit from DL13, a 2000kVA three-phase, medium-voltage, dry-type transformer with a 125kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The following observations can be made about this scatter plot:

- The current standard efficiency level of 99.15 percent is met by designs using M5 core steel or better, though it can be met with M6 core steel designs at a higher price.
- The amorphous metal (SA1) core is the most cost-effective designs for any efficiency level above 99.43 percent, and can reach efficiencies above 99.65 percent.

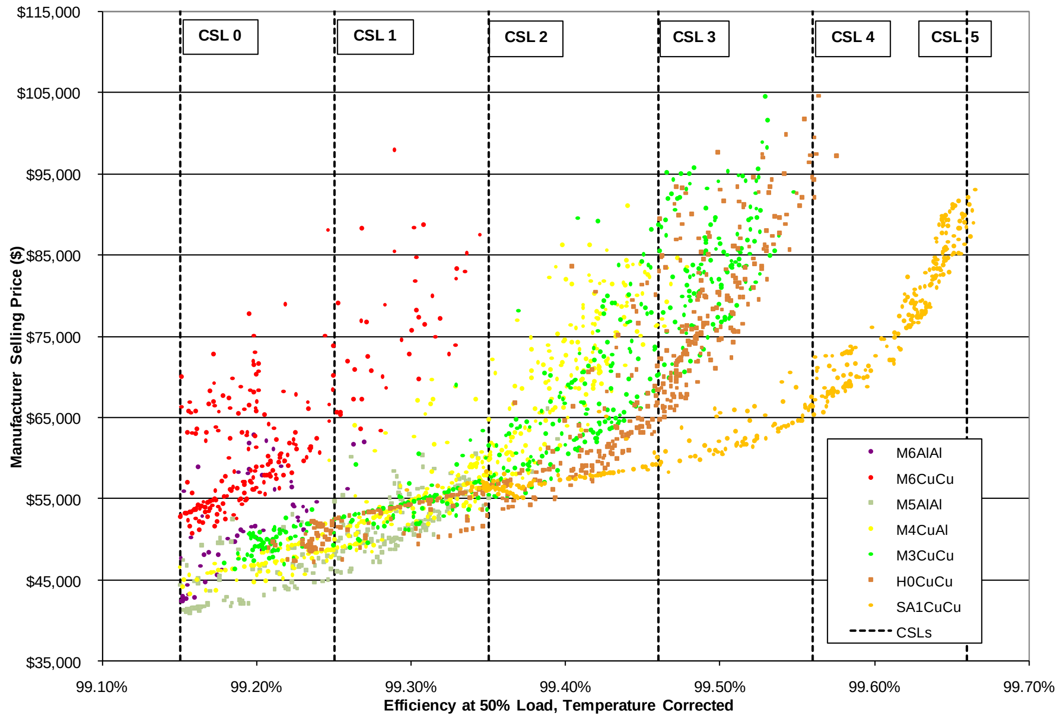

Figure 5.6.13 Engineering Analysis Results, Design Line 13

5.6.2 Symmetric Core Designs for the Reference Case

The designs in this section represent the symmetric core designs that DOE analyzed in the life-cycle cost and national impact analyses. As mentioned in section 5.3.3.2, DOE simulated symmetric core designs by adjusting design parameters from each of its traditional core designs in the reference case. This section presents graphs showing the traditional core designs and the symmetric core designs. Since the symmetric core designs yielded greater efficiencies than the original, traditional core designs, DOE considered an additional CSL for the max-tech efficiency level.

Figure 5.6.14 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL4, a 150kVA three-phase, liquid-immersed transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. These symmetric core designs do not account for a tertiary winding, but rather analyze the cost-efficiency relationship of symmetric cores for the subgroup of distribution transformers that would not require a tertiary winding. The maximum efficiency achievable using a symmetric core design is 99.65 percent, represented by CSL 7.

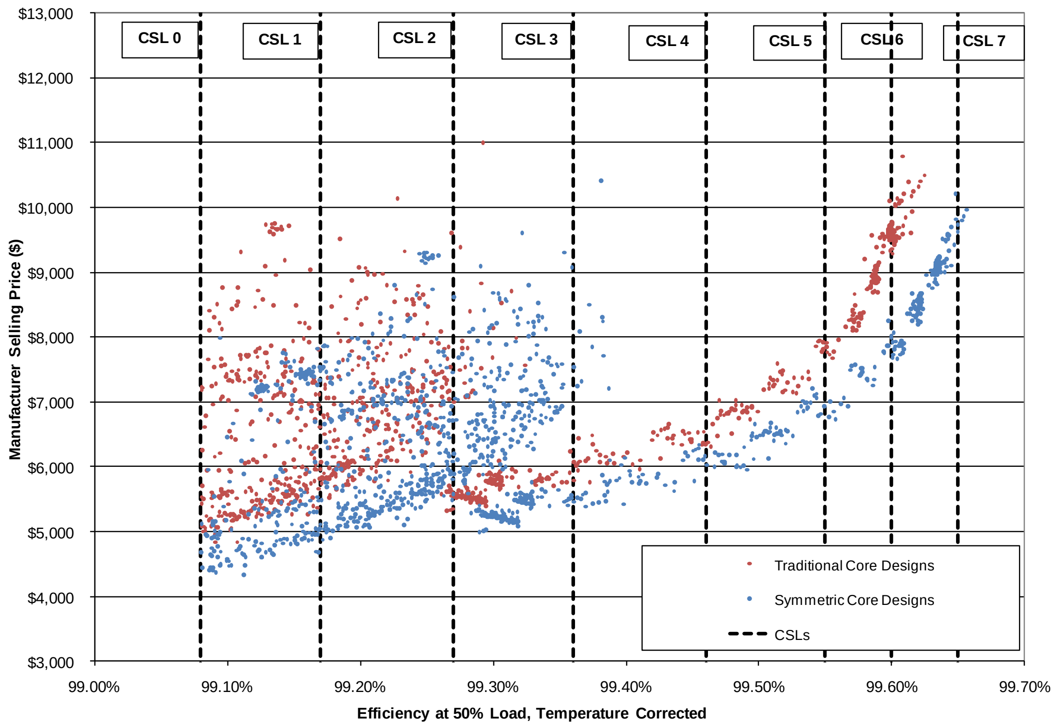

Figure 5.6.14 Symmetric Core Engineering Analysis Results, Design Line 4

Figure 5.6.15 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL5, a 1500kVA three-phase, liquid-immersed transformer. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. These symmetric core designs do not account for a tertiary winding, but rather analyze the cost-efficiency relationship of symmetric cores for the subgroup of distribution transformers that would not require a tertiary winding. The maximum efficiency achievable using a symmetric core design is 99.75 percent, represented by CSL 7.

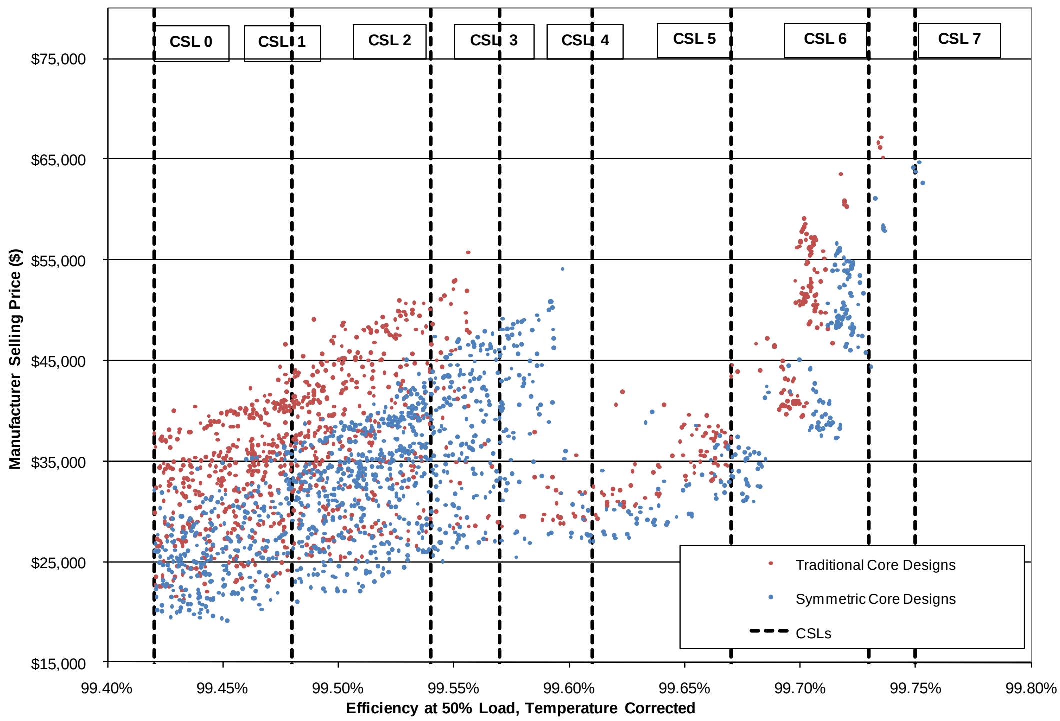

Figure 5.6.15 Symmetric Core Engineering Analysis Results, Design Line 5

Figure 5.6.16 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL7, a 75kVA three-phase, low-voltage, dry-type distribution transformer. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.48 percent, represented by CSL 8.

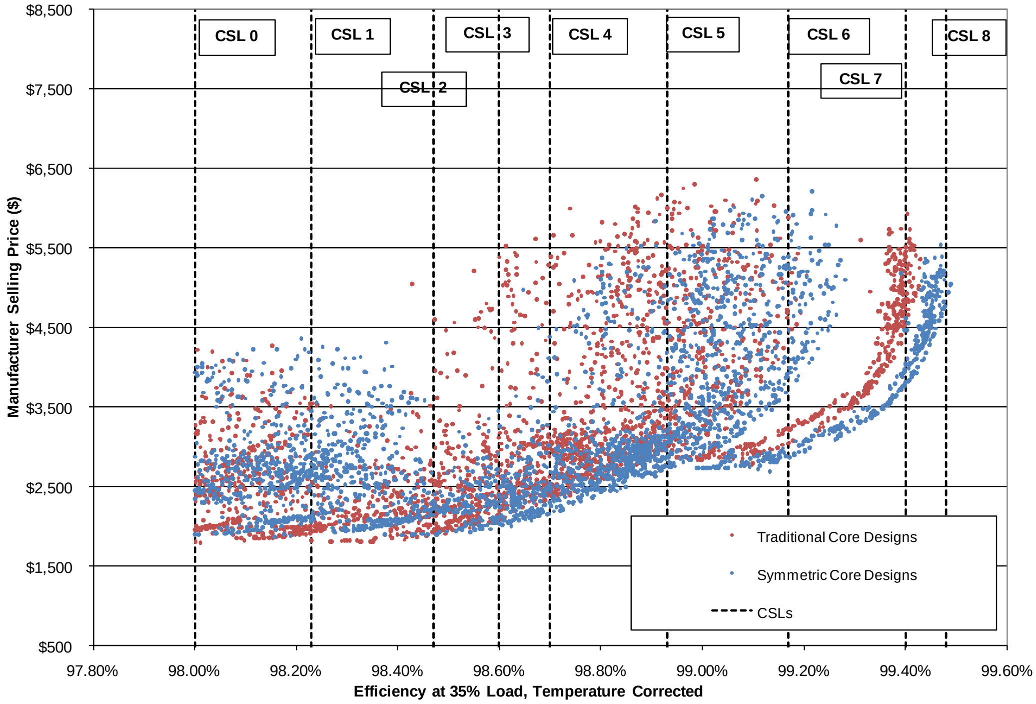

Figure 5.6.16 Symmetric Core Engineering Analysis Results, Design Line 7

Figure 5.6.17 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL8, a 300kVA three-phase, low-voltage, dry-type distribution transformer. The efficiency levels shown in this plot represent transformers at 35 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.63 percent, represented by CSL 6.

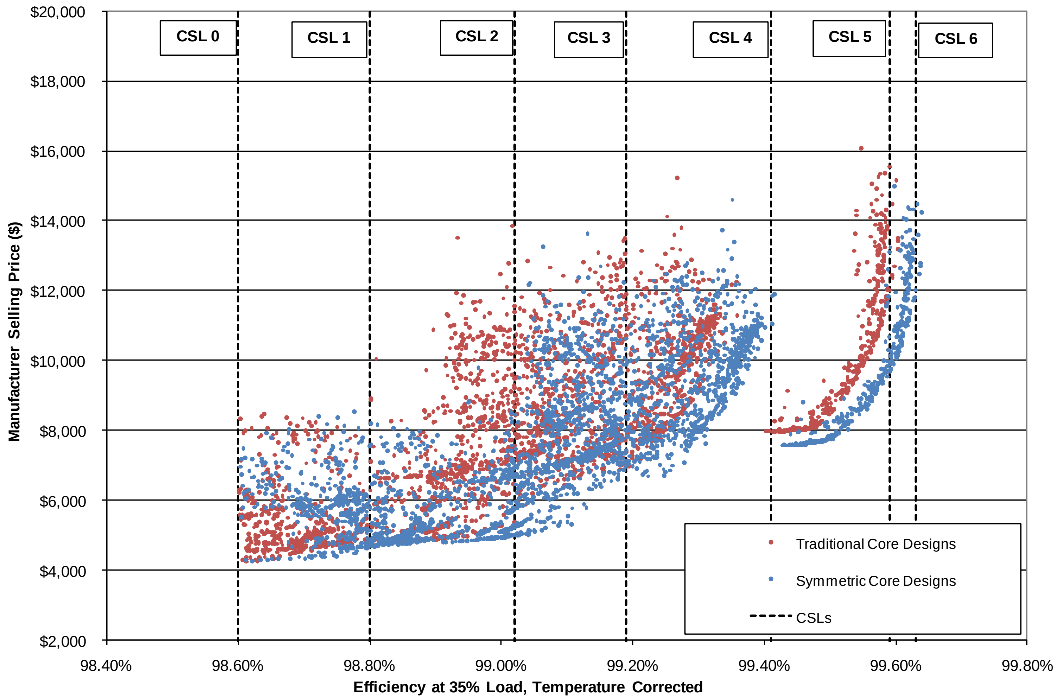

Figure 5.6.17 Symmetric Core Engineering Analysis Results, Design Line 8

Figure 5.6.18 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL9, a 300kVA three-phase, medium-voltage, dry-type distribution transformer with a 45kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.62 percent, represented by CSL 6.

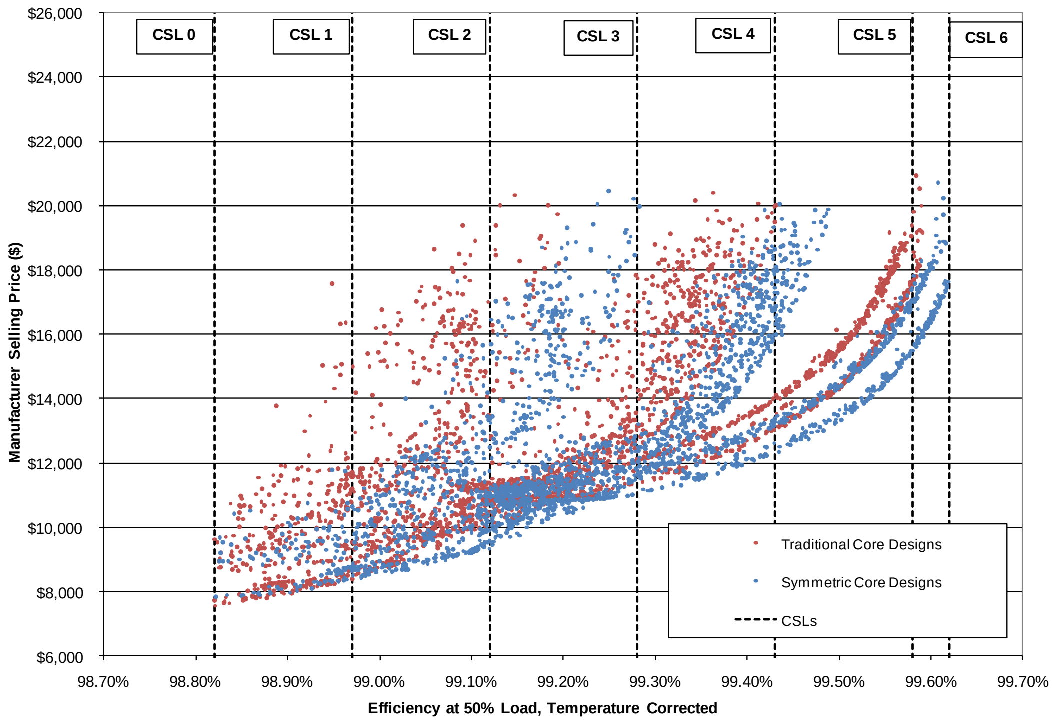

Figure 5.6.18 Symmetric Core Engineering Analysis Results, Design Line 9

Figure 5.6.19 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL10, a 1500kVA three-phase, medium-voltage, dry-type distribution transformer with a 45kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.71 percent, represented by CSL 6.

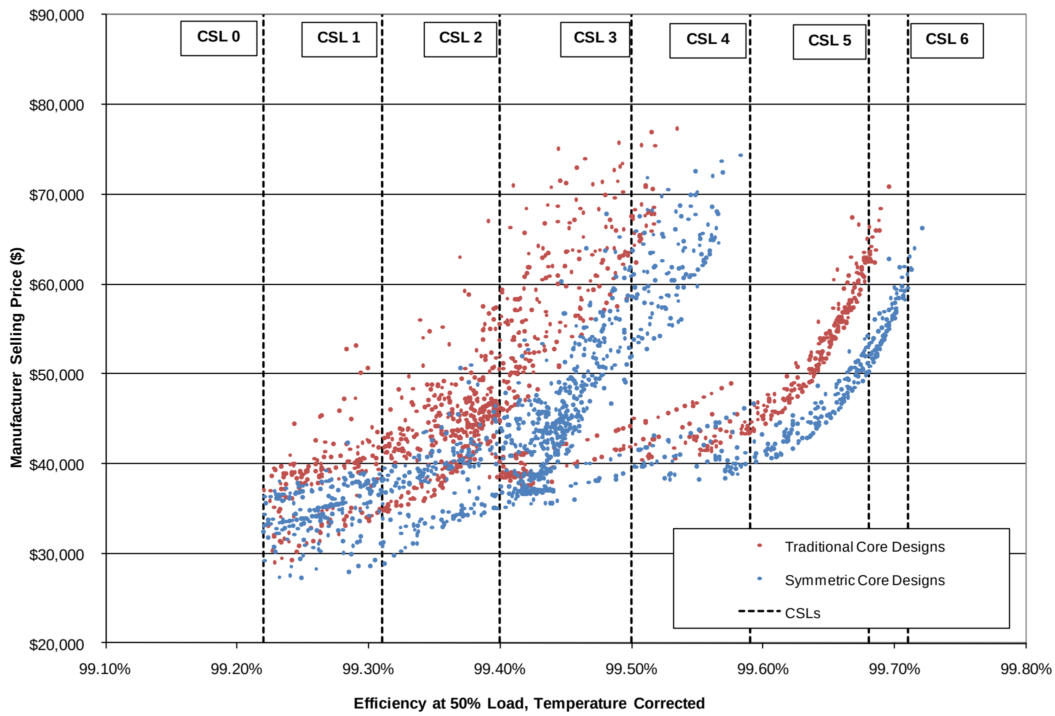

Figure 5.6.19 Symmetric Core Engineering Analysis Results, Design Line 10

Figure 5.6.20 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL11, a 300kVA three-phase, medium-voltage, dry-type distribution transformer with a 95kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.55 percent, represented by CSL 6.

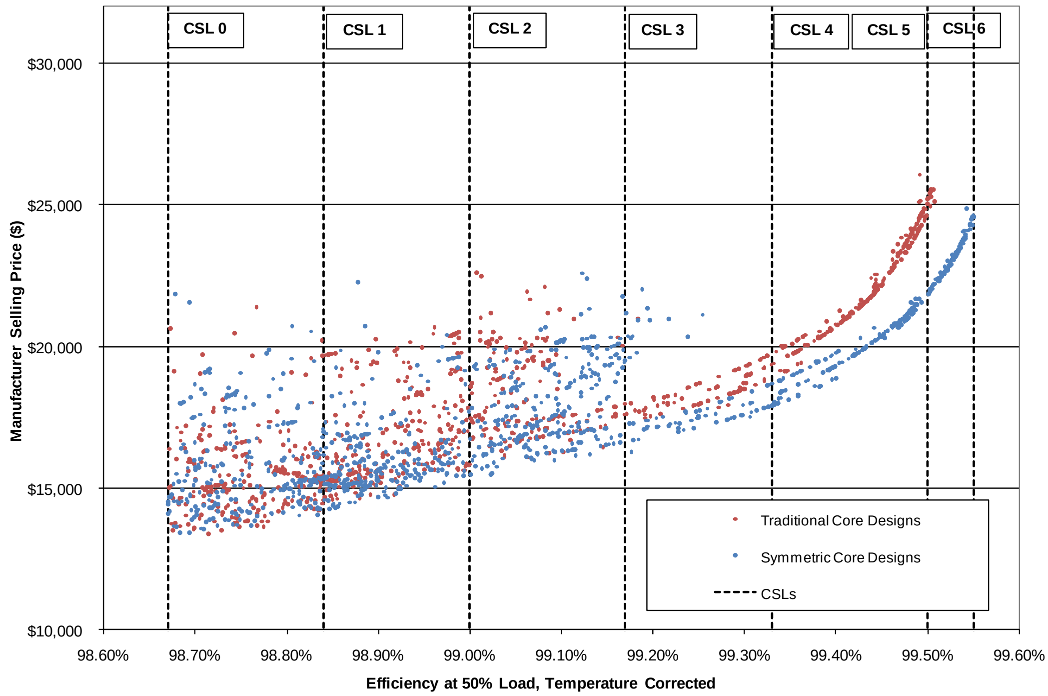

Figure 5.6.20 Symmetric Core Engineering Analysis Results, Design Line 11

Figure 5.6.21 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL12, a 1500kVA three-phase, medium-voltage, dry-type distribution transformer with a 95kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.69 percent, represented by CSL 7.

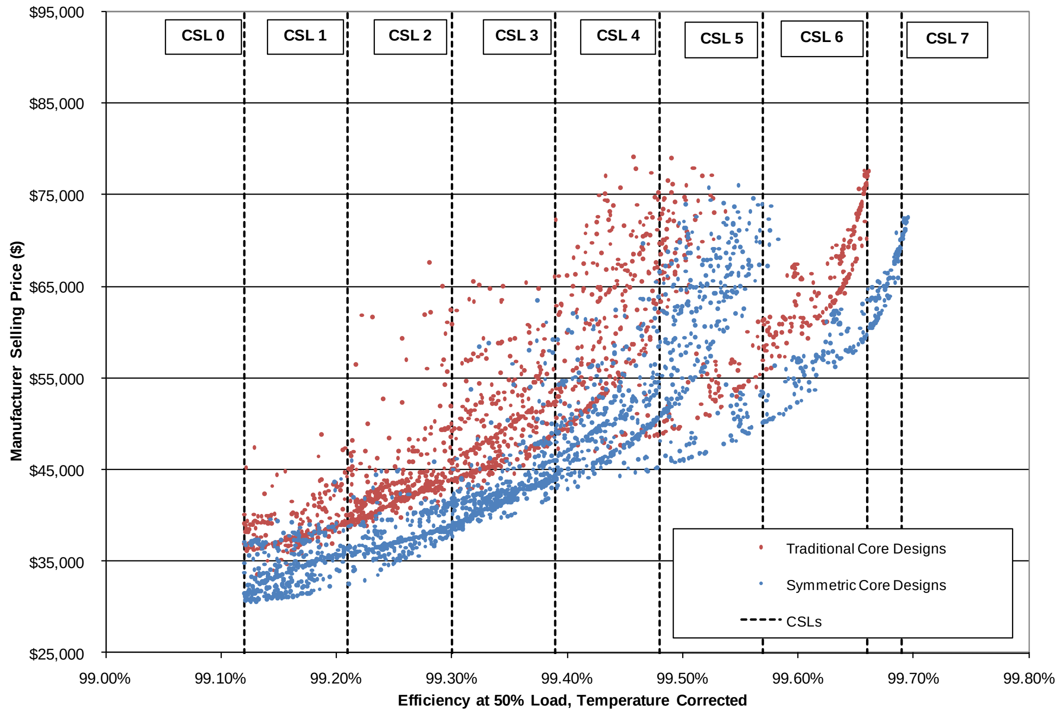

Figure 5.6.21 Symmetric Core Engineering Analysis Results, Design Line 12

Figure 5.6.22 presents a plot of the manufacturer sales prices and efficiency levels for the simulated symmetric core designs compared to the traditional core designs for the representative unit from DL13, a 2000kVA three-phase, medium-voltage, dry-type distribution transformer with a 125kV BIL. The efficiency levels shown in this plot represent transformers at 50 percent of nameplate load and are corrected for temperature. The maximum efficiency achievable using a symmetric core design is 99.69 percent, represented by CSL 6.

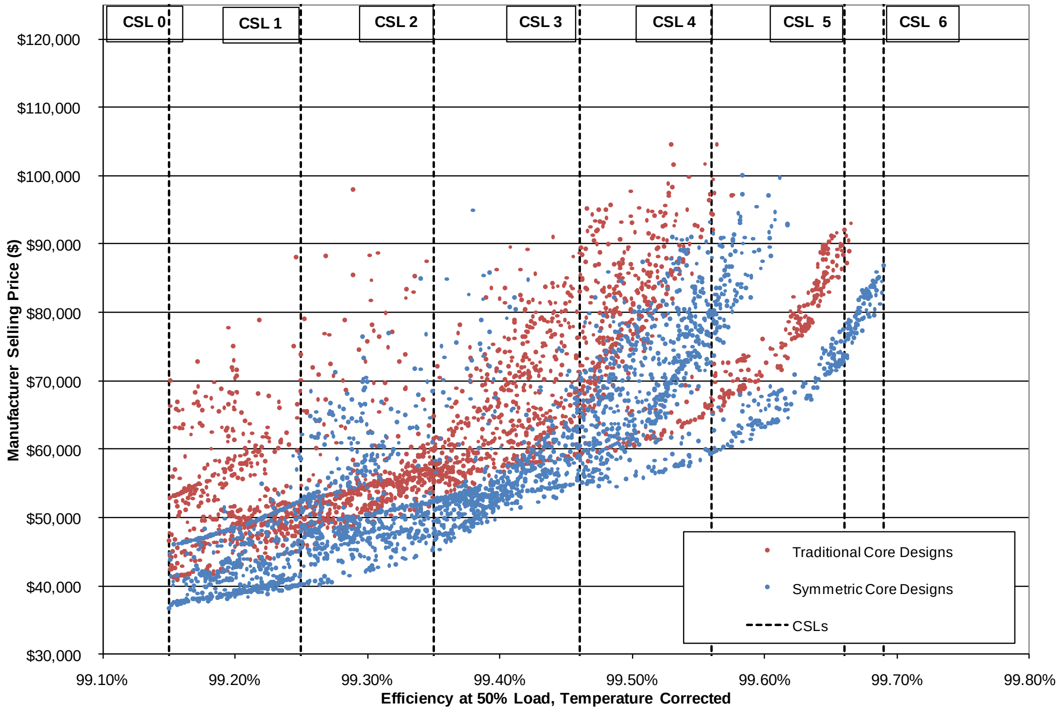

Figure 5.6.22 Symmetric Core Engineering Analysis Results, Design Line 13

5.6.3 Supplemental Designs Using Aluminum Conductors, Non-Reference Case

The designs in this section represent the supplemental traditional core designs using aluminum conductors that DOE modeled. As mentioned in section 5.3.19, these designs were not prepared in time for DOE to analyze them as part of its LCC or NIA. However, DOE presents the designs to solicit feedback on the cost-efficiency relationship of these designs compared to the reference case designs presented in section 5.6.1. In Figure 5.6.23 to Figure 5.6.27, DOE presents the cost-efficiency relationship of the liquid-immersed supplemental designs compared to the reference case designs. In Figure 5.6.28 through Figure 5.6.30, DOE presents the cost-efficiency relationship of the low-voltage dry-type supplemental designs compared to the reference case designs. Figure 5.6.31 to Figure 5.6.35 presents the designs for medium-voltage dry-type design lines. In each figure, the supplemental designs are designated in the legend below the "CSLs" entry.

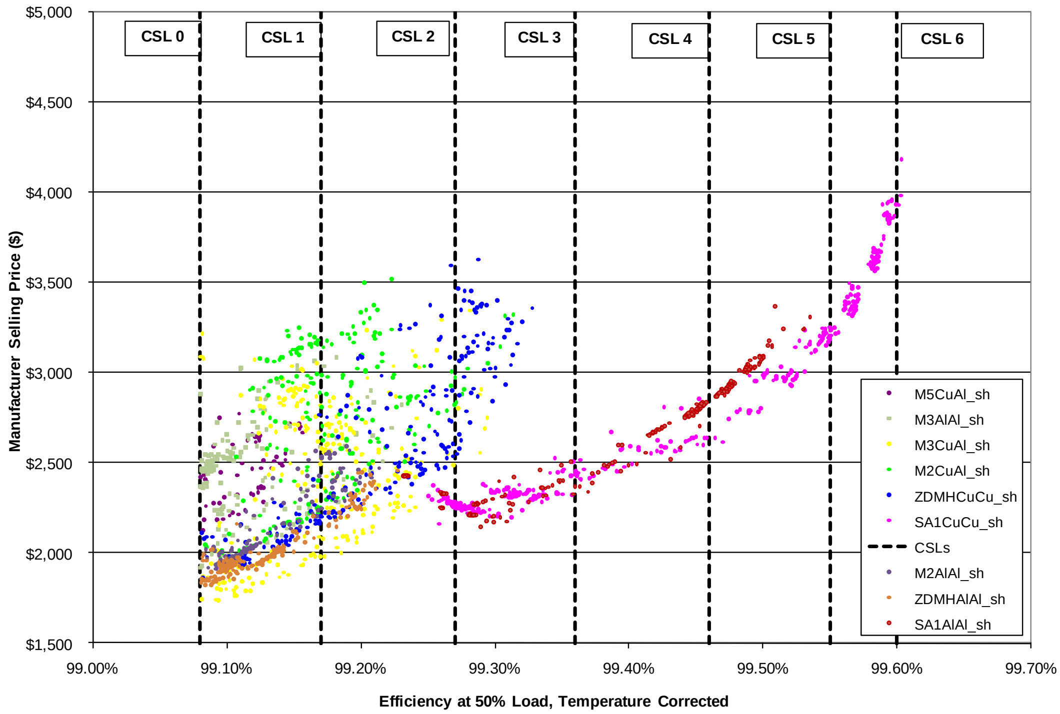

Figure 5.6.23 Supplemental vs. Reference Case Designs for Design Line 1

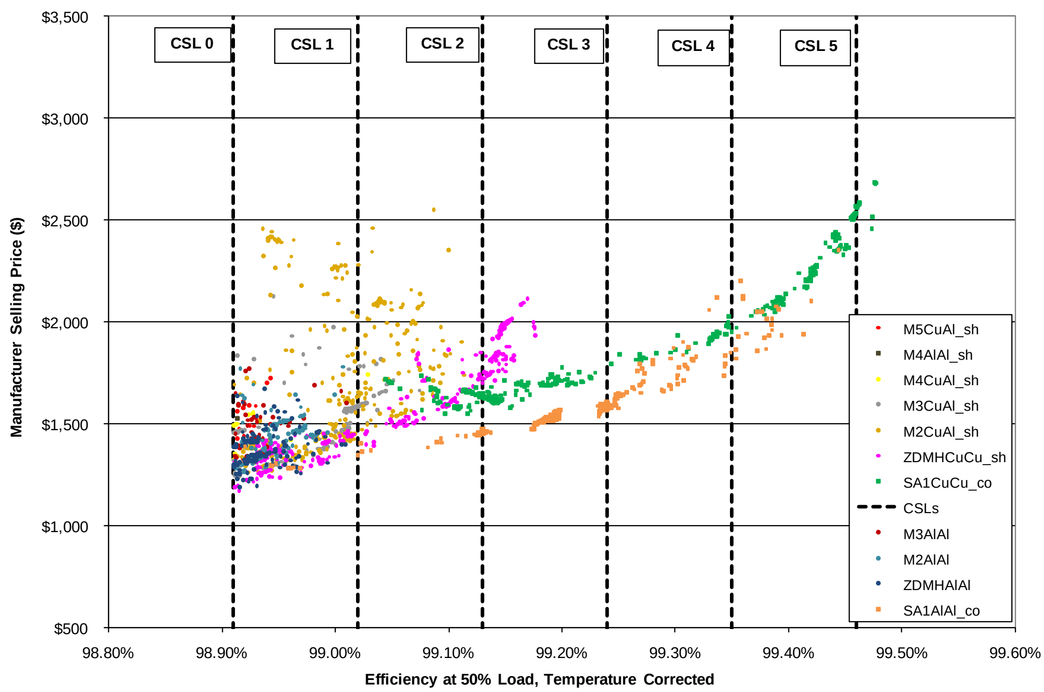

Figure 5.6.24 Supplemental vs. Reference Case Designs for Design Line 2

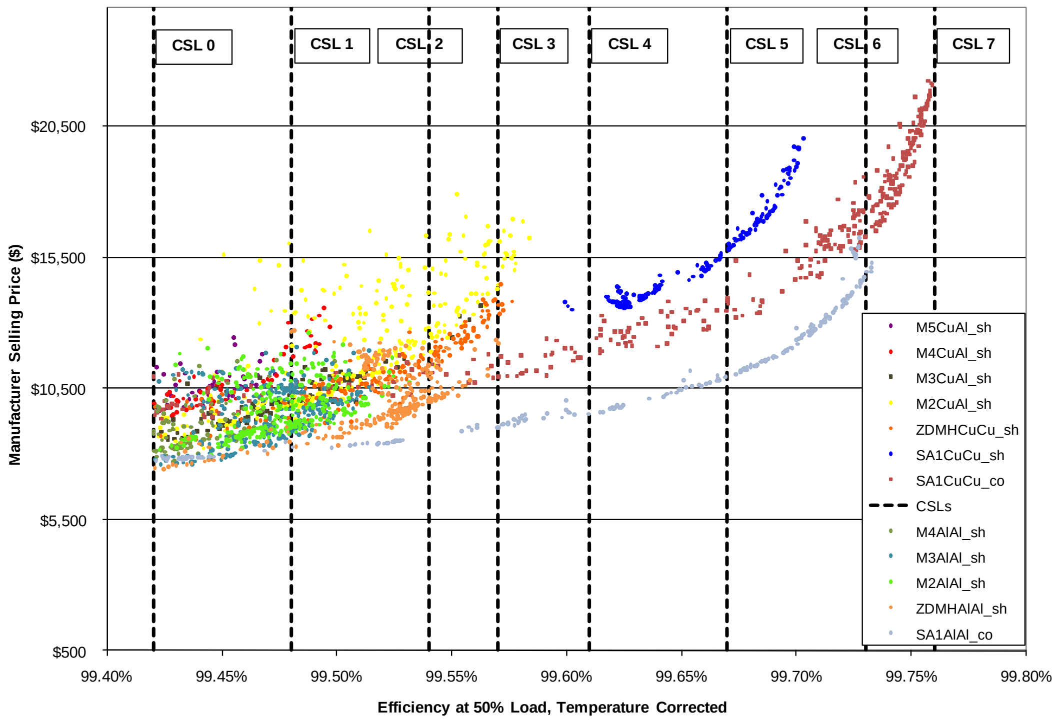

Figure 5.6.25 Supplemental vs. Reference Case Designs for Design Line 3

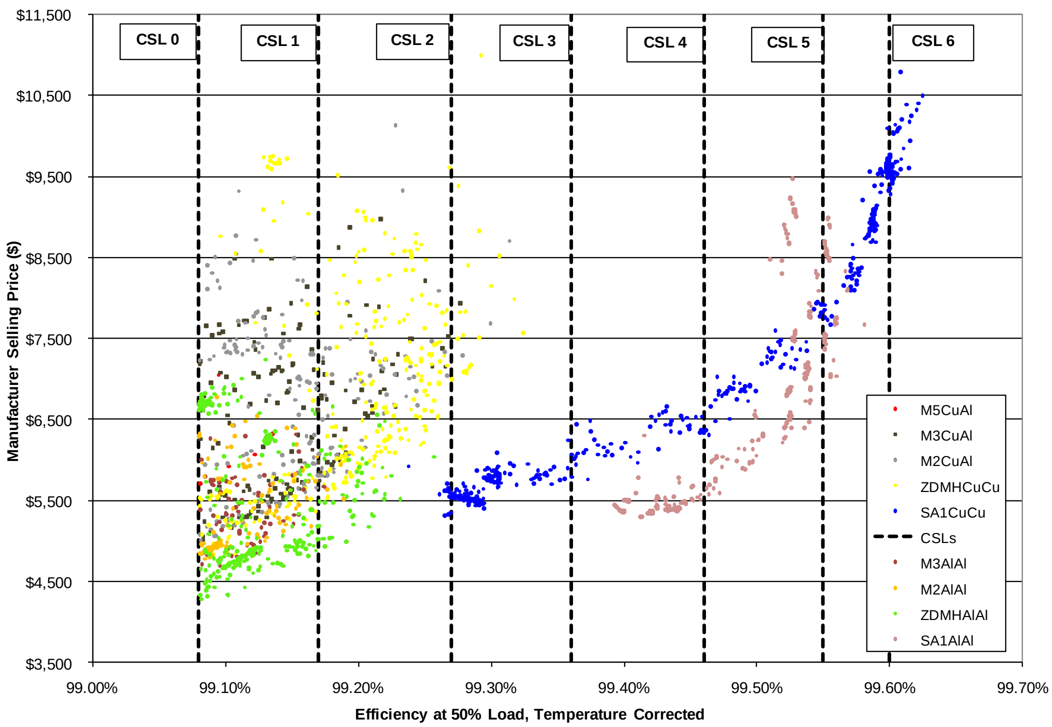

Figure 5.6.26 Supplemental vs. Reference Case Designs for Design Line 4

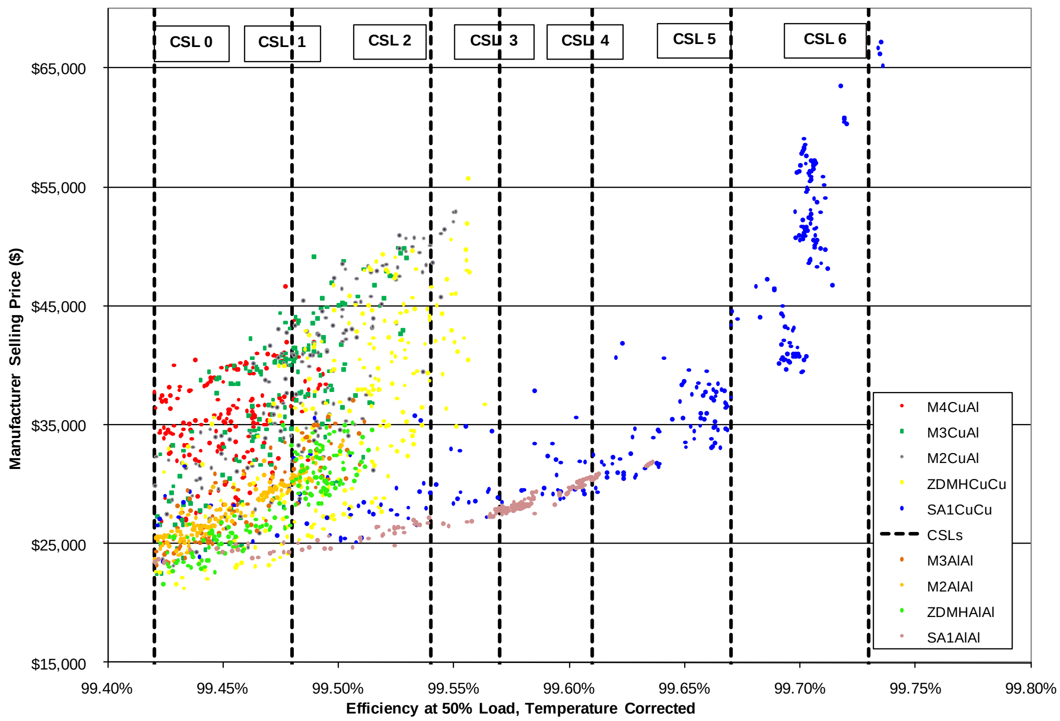

Figure 5.6.27 Supplemental vs. Reference Case Designs for Design Line 5

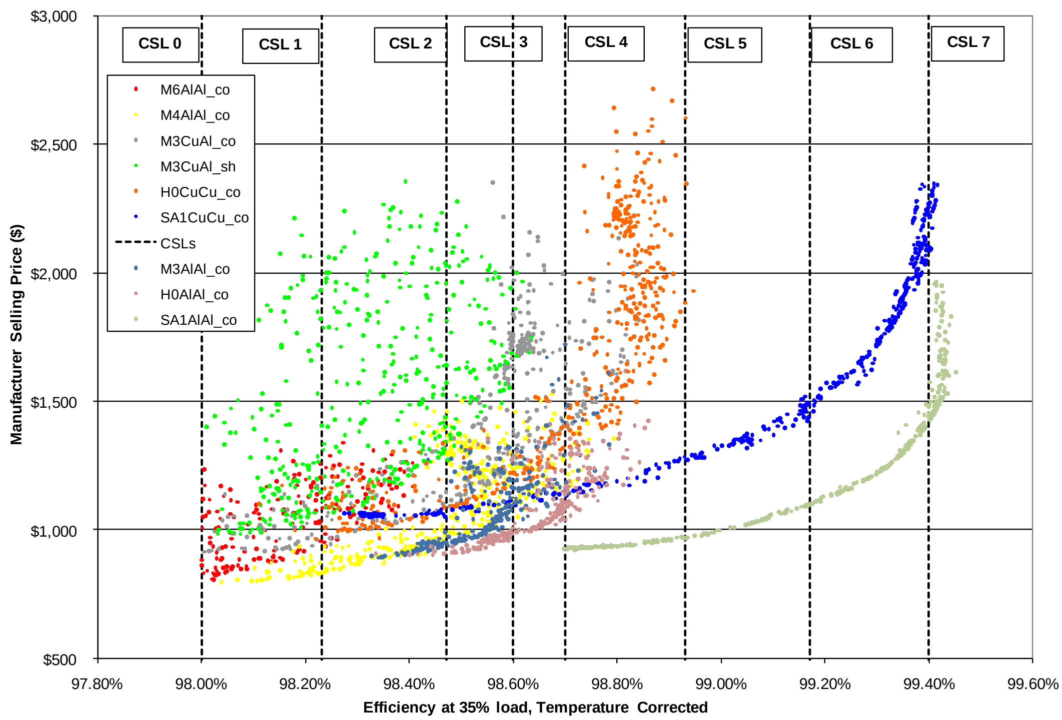

Figure 5.6.28 Supplemental vs. Reference Case Designs for Design Line 6

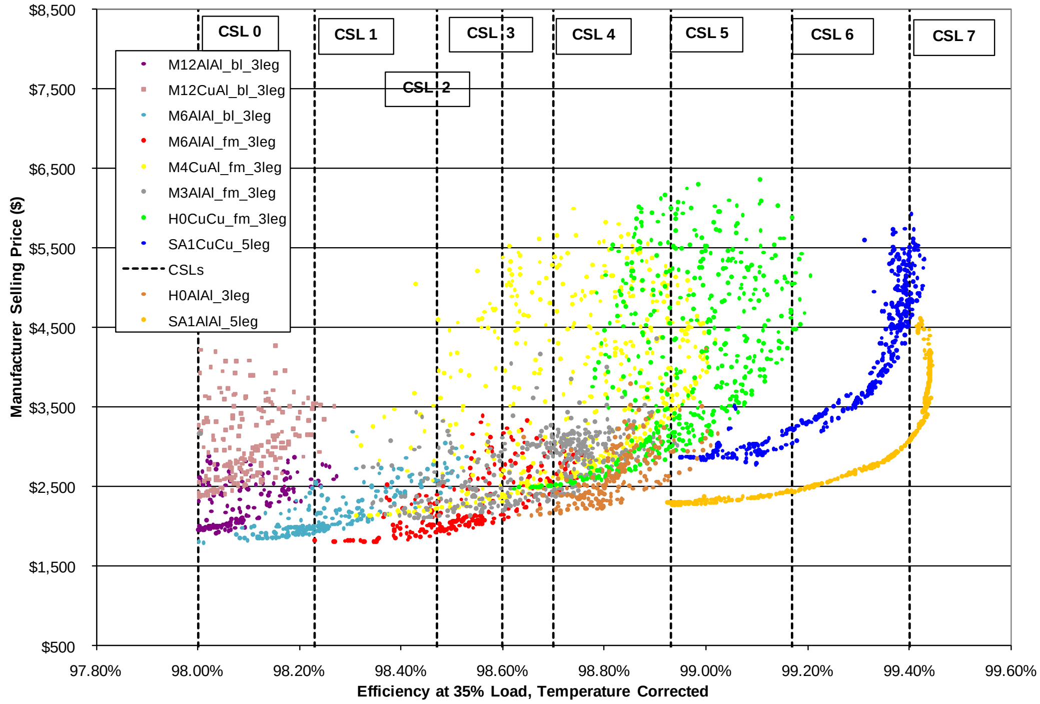

Figure 5.6.29 Supplemental vs. Reference Case Designs for Design Line 7

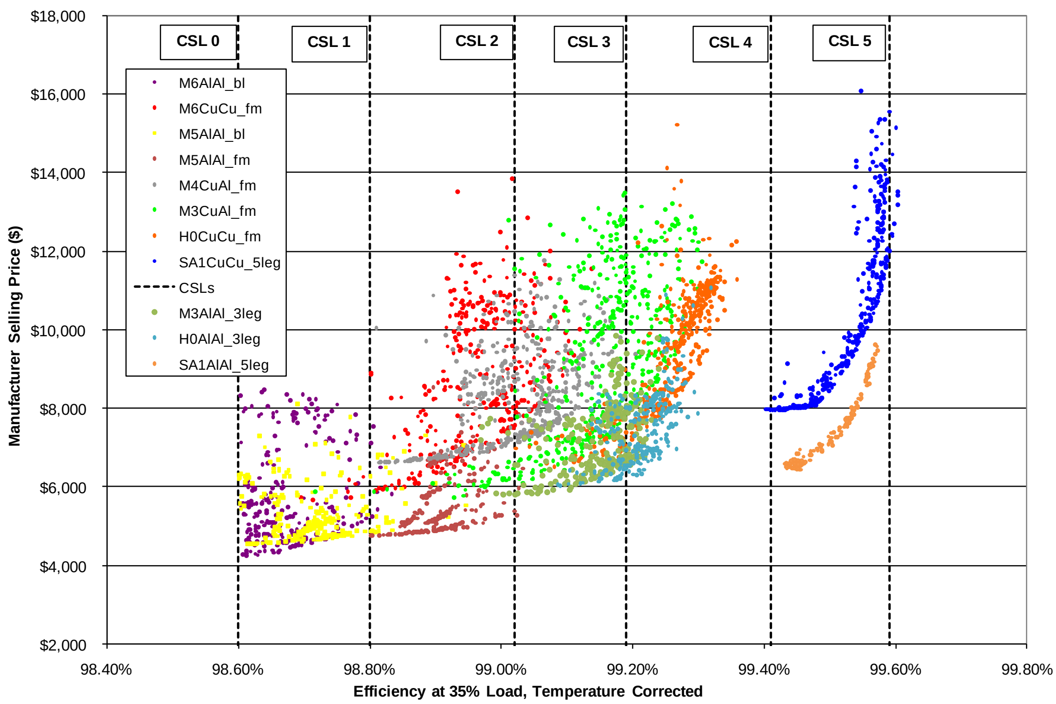

Figure 5.6.30 Supplemental vs. Reference Case Designs for Design Line 8

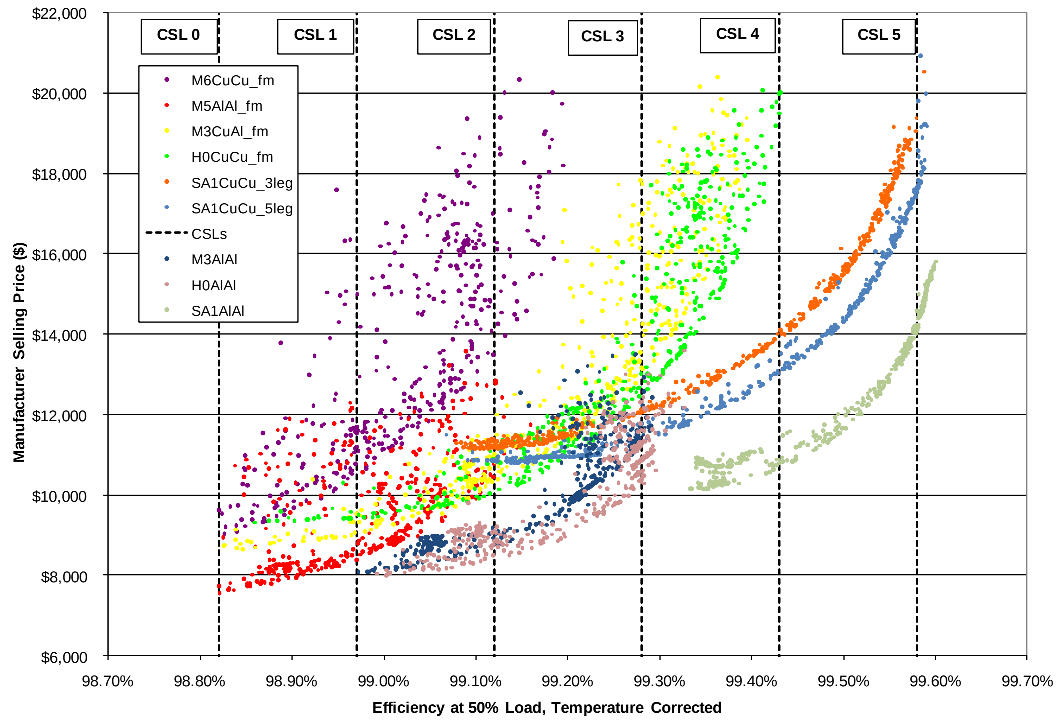

Figure 5.6.31 Supplemental vs. Reference Case Designs for Design Line 9

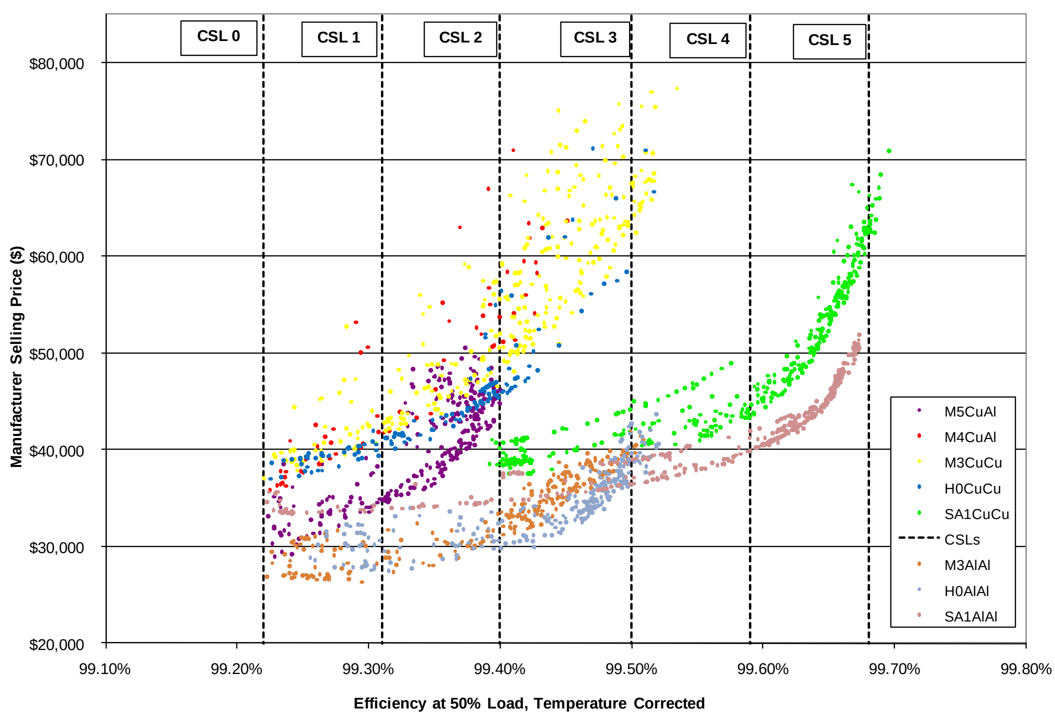

Figure 5.6.32 Supplemental vs. Reference Case Designs for Design Line 10

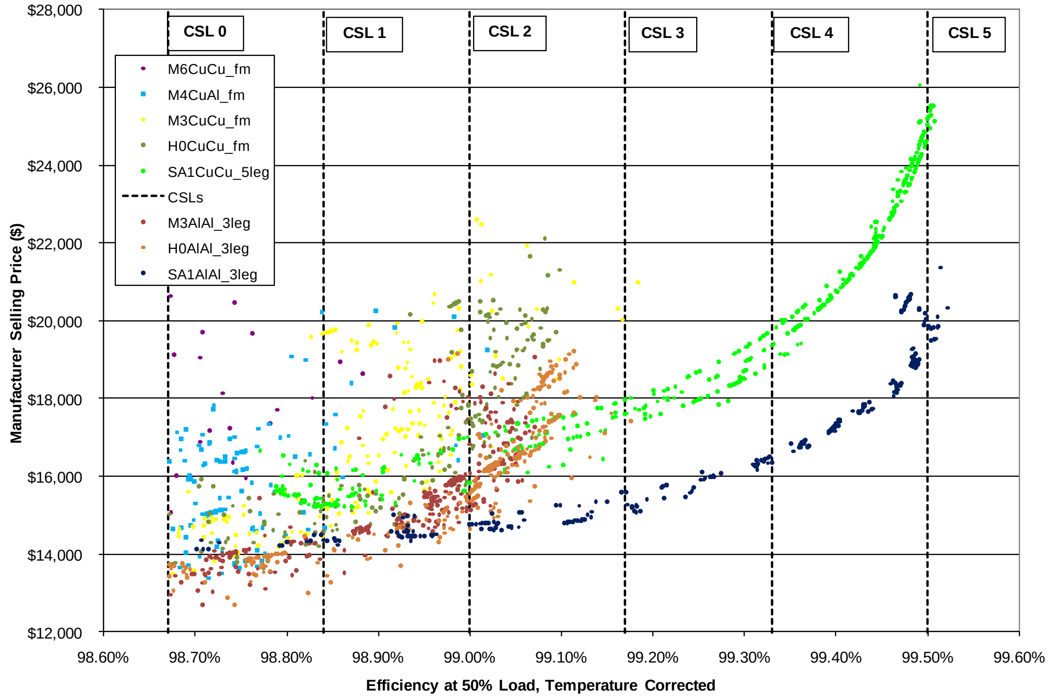

Figure 5.6.33 Supplemental vs. Reference Case Designs for Design Line 11

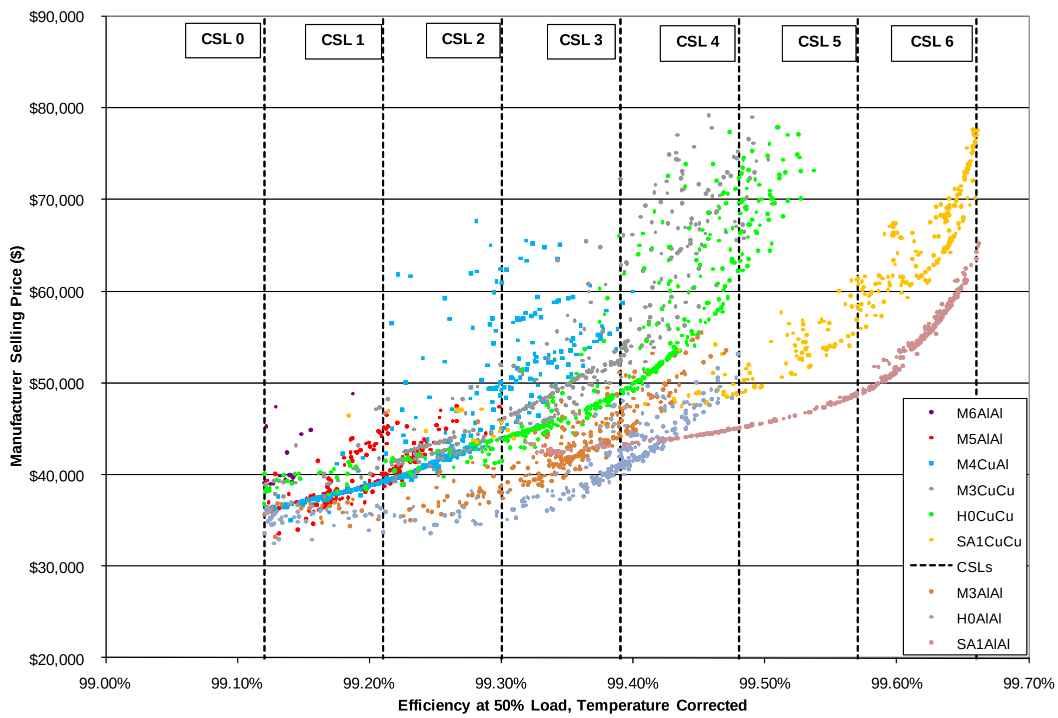

Figure 5.6.34 Supplemental vs. Reference Case Designs for Design Line 12

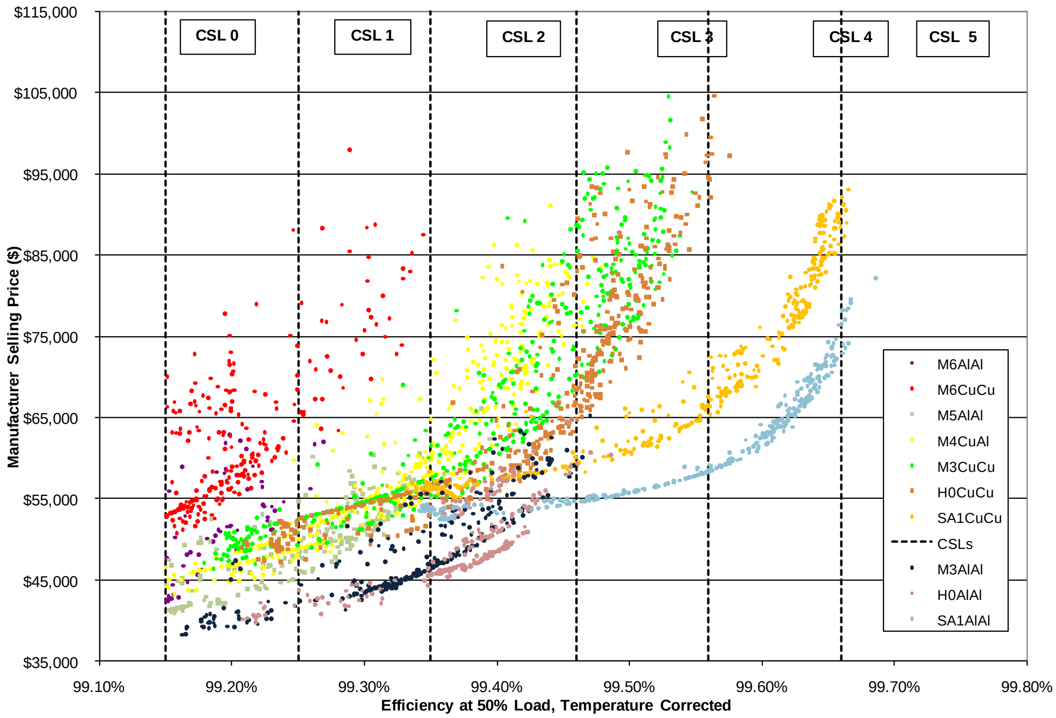

Figure 5.6.35 Supplemental vs. Reference Case Designs for Design Line 13

5.7 THREE EXAMPLE TRANSFORMER DESIGNS AND COST BREAKDOWNS

This section presents some of the OPS transformer designs from DOE's Engineering Analysis database. As discussed earlier, to prepare a cost-efficiency relationship on selected representative units, DOE contracted Optimized Program Service (OPS), a software company specializing in transformer design since 1969. Using a range of input parameters and material prices, more than 43,000 transformer designs were created by OPS for DOE's analysis. For each design, the software generates specific information about the core and coil, including physical characteristics, dimensions, material requirements and mechanical clearances, as well as a complete electrical analysis of the final design. For information on OPS and their software, visit their website: http://www.opsprograms.com/home.html.

To illustrate the typical output from the OPS software, a design from each of the three superclasses (*i.e.*, liquid-immersed, low-voltage dry-type and medium-voltage dry-type) are presented in this section. As these practical designs illustrate, the software output is used to create a bill of materials, which is marked-up to arrive at the manufacturer's selling price. The OPS software provides an electrical analysis including efficiency, which, when plotted with the manufacturer's selling price, constitutes the primary output of the engineering analysis.

The three distribution transformers presented are from three design lines – 1, 7, and 12. Across all the design lines, the complete database of designs contains 43,512 distribution transformer specification and winding sheets, bills of materials, and performance reports. Any infeasible designs or designs below the minimum efficiency standard are removed and then this design database is used by the LCC analysis (see Chapter 8) as it simulates purchases of distribution transformers in the marketplace.

- ***Design Line 1*:** 50 kVA single-phase, liquid-immersed. M2 core steel with copper primary and aluminum secondary windings (M2CuAl) at a \$3.00 A and a \$1.20 B evaluation formula.

- ***Design Line 7***: 75 kVA three-phase, low-voltage dry-type. M6 buttlap core steel with aluminum primary and secondary windings (M6AlAl) at a \$0.50 A and a \$0.10 B evaluation formula.

- ***Design Line 12***: 1500 kVA three-phase, medium-voltage dry-type. M4 core steel with copper primary and aluminum secondary windings (M4CuAl) at a \$1.50 A and a \$0.30 B evaluation formula.

For the three designs presented, the design detail report is followed by a bill of materials showing the cost calculation, and a pie chart providing a breakdown of the final selling price.

5.7.1 Design Details Report for Transformer from Design Line 1

A design specification report for a 50kVA single-phase liquid-immersed transformer appears below. This design incorporates M2 core steel, with a copper primary and an aluminum secondary. The evaluation factors for this design are \$3.00 A and \$1.20 B. The bill of materials and associated breakdown of costs for this design are also reported, after the design and electrical analysis reports.

OPTIMIZED PROGRAM SERVICE

CLEVELAND OHIO 101800

2010-10-20 10:54:54

DESIGN ID DL1PM2CUAL-(3,1.2)

DG-CORE SHELL TYPE TRANSFORMER

FREQUENCY 60.0 KVA RATING 50.00 @ 100.00% DUTY CYCLE

CORE DG-M2 M2 THICKNESS .0070

D: 7.625 E: 2.000 F: 3.500 G: 8.875
EFF. AREA 28.98 WEIGHT 248.175

WNDG FORM: INS. DIM. 7.875 × 4.180 THICKNESS 0.070 LENGTH 8.375

COIL SPECIFICATIONS

WNDG	WIRE			LENGTH	MEAN TURNS	MARGIN	WT
S1	0.036× 7.625		AL	34.26	27.41	0.375	11.011
P1	1× 1 #14	ROUND	H CU	5957.88	37.83	0.375	74.311
S2	0.036× 7.625		AL	60.23	48.19	0.375	19.359

NUMBER OF COILS 1

TOTAL BARE CONDUCTOR WEIGHT 104.681
TOTAL INSULATION WEIGHT 4.341

WNDG	TURNS	LO TAP	HI TAP	LAYRS	T/L	LAYR INS	SEC. INS	BUILD
S1	15.0			15	1.0	1(0.0050)	1(0.0300)	0.610
P1	1800.0	1710.0	1890.0	18	107.0	4(0.0050)	1(0.1000)	1.555
S2	15.0			15	1.0	1(0.0050)	1(0.0500)	0.610

TOTAL BUILD(%) 86.42

WNDG	TAPS: TURNS(VOLTS)	
P1	1755.0(14040.00)	1845.0(14760.00)

WNDG	INTERNAL DUCTS(100.00)		%EFF	EXTERNAL DUCTS(100.00)	%EFF
S1	3	0.125 × 0.125	END		
P1	6	0.125 × 0.125	END	0.125 × 0.125	END
S2	1	0.125 × 0.125	END	0.125 × 0.125	END

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	14400.00	13680.00	15120.00	34.5	3.513	14.99559	1085.47	
S1	119.02	120.00	NLV	10.0	208.330	0.00167	759.71	0.8
S2	118.70	120.00	NLV	10.0	208.330	0.00293	759.71	1.1

	F.L.	N.L.		
FLUX DENS.	15.987	16.058	DESTRUCTION FACTOR	1.050
CORE LOSS	117.473	119.254	LEAKAGE INDUCTANCE MHYS	193.825
COIL LOSS	480.542	0.005	POWER FACTOR	1.000
EXCIT. VA	233.210	240.823	IMPEDANCE %	1.99
EXCIT. CURR.	0.016	0.017	EFFICIENCY %	98.82
			TANK OIL	18.86 GAL.
			OIL WEIGHT	143.69 LB.

AMBIENT TEMP.	20.00	NOMINAL LENGTH	15.090
TEMP.RISE	59.32	NOMINAL DEPTH	17.875
OPERATING TEMP.	79.32	NOMINAL HEIGHT	12.875

	S1	P1	S2
GRADIENT:	0.9	4.2	2.6

AVG. OIL RISE: 53.
TOP OIL RISE: 72.4

SHAPE	TOTAL COOLING AREA	TANK AREA	RAD. AREA	RAD. OIL/GAL.	TYPE
RECTG.	1354.894	1354.894	0.000	0.000	C

TANK DIMENSIONS

LENGTH = 16.090
DEPTH = 18.875
OIL HEIGHT = 19.375

COND. I^2R LOSS = 465.4741
COND. EDDY CURRENT LOSS = 3.4305
OTHER STRAY LOSS = 11.6369
K VALUE = 1.0000
% LOSS = 2.5000

AT REFERENCE TEMP. 85.0^{o}

COIL LOSS = 489.332
IMPEDANCE % = 2.002

% LOAD	% REG	% EFF	% IR	% IX	% IZ	CORE	LOAD LOSS	TEMP RISE
5	0.04	95.41	0.040	0.093	0.101	119.18	1.07	14.7
10	0.08	97.59	0.078	0.181	0.197	119.10	4.18	15.1
15	0.12	98.32	0.116	0.269	0.293	119.03	9.36	15.7
20	0.16	98.66	0.154	0.357	0.389	118.95	16.62	16.5
25	0.20	98.85	0.193	0.446	0.486	118.87	26.02	17.5
30	0.24	98.97	0.233	0.534	0.583	118.79	37.60	18.8
35	0.29	99.04	0.273	0.623	0.680	118.71	51.43	20.2
50	0.42	99.11	0.398	0.889	0.974	118.47	107.08	26.0
60	0.51	99.09	0.486	1.067	1.172	118.29	156.92	30.9
65	0.56	99.07	0.531	1.156	1.272	118.20	186.00	33.7
75	0.66	99.02	0.627	1.334	1.474	118.01	253.11	39.9
80	0.72	98.99	0.677	1.424	1.576	117.91	291.44	43.4
100	0.95	98.82	0.894	1.783	1.994	117.47	480.54	59.3
125	1.22	98.61	1.140	2.233	2.507	116.97	765.97	65.0

Table 5.7.1 provides the bill of materials which was calculated from the OPS design details report. This bill of materials uses the raw material prices given in this chapter for fixed and variable materials used in building the transformer. These materials are then marked-up at the bottom of the table to arrive at the manufacturer's selling price. This table provides the bill of materials for a transformer from design line 1, a 50kVA single-phase, liquid-immersed, pad-

mount M2 design, with a copper primary and an aluminum secondary. This design was generated using a $3.00A and $1.20B.

Table 5.7.1 Bill of Materials for Transformer from Design Line 1

Bill of Materials and Labor for liquid-immersed, single-phase, pad-mount, 50kVA				
A$ Input		$3.00		
B$ Input		$1.20		
Efficiency at 50% load		99.10%		
Material Item	**Type**	**Quantity**	**$ Each**	**$ Total**
Core Steel* (lb)	M2-.007	248.18	$2.00	$496.36
Primary winding* (lb)	Copper wire, formvar, round #10-20	74.31	$3.94	$292.78
Secondary windings* (lb)	Aluminum strip, thickness range 0.02-0.045	30.37	$1.57	$47.68
Winding form & insulation* (lb)	Kraft insulating paper with diamond adhesive	4.34	$1.52	$6.60
Oil (gal)	-	18.86	$3.35	$63.18
Tank	-	1	$140.34	$140.34
Core clamp	-	1	$15.00	$15.00
Nameplate	-	1	$0.65	$0.65
Bushings	HV & LV	1	$34.00	$34.00
Misc. hardware	-	1	$10.00	$10.00
Scrap Factor			1.0%	$8.43
Total Material Cost				$1,115
Total Material Weight (lb)		672		
Labor item		**Hours**	**Rate**	**$ Total**
Lead dressing		0.50	51.52	$25.76
Inspection		0.10	51.52	$5.15
Baking Coils		0.10	51.52	$5.15
Tanking and impregnating		0.50	51.52	$25.76
Preliminary test		0.10	51.52	$5.15
Final test		0.15	51.52	$7.73
Pallet loading		0.27	51.52	$13.91
Marking and miscellaneous		0.28	51.52	$14.43
Winding the primary		0.19	51.52	$9.79
Winding the secondary		0.45	51.52	$23.18
Cutting, forming, and annealing		0.78	51.52	$40.19
Core assembly		0.29	51.52	$14.94
Handling and slitting factor (on material)			1.50%	$12.65
Total Labor		3.70	51.52	$203.28
Manufacturing Cost (Material + Labor)				$1,318
Factory Overhead (Materials only)		12.5%		$139
Shipping Cost (Based on Total Weight)		$0.22/lb		$148
Non-production Cost Markup		25.0%		$401
Manufacturer Selling Price**				$2,007

* Indicates those items to which the scrap factor (1.0%) and the handling and slitting factor (1.5% are applied.
** Price based on rounded estimations. The non-rounded price may vary slightly.

Figure 5.7.1 provides a summary of the costs contributing to the total selling price of the transformer from design line 1. For this design, approximately 56 percent of the final manufacturer selling price is direct material and scrap. Labor accounts for 10 percent of the price, factory overhead accounts for 7 percent, and together, shipping and non-production costs account for 27 percent.

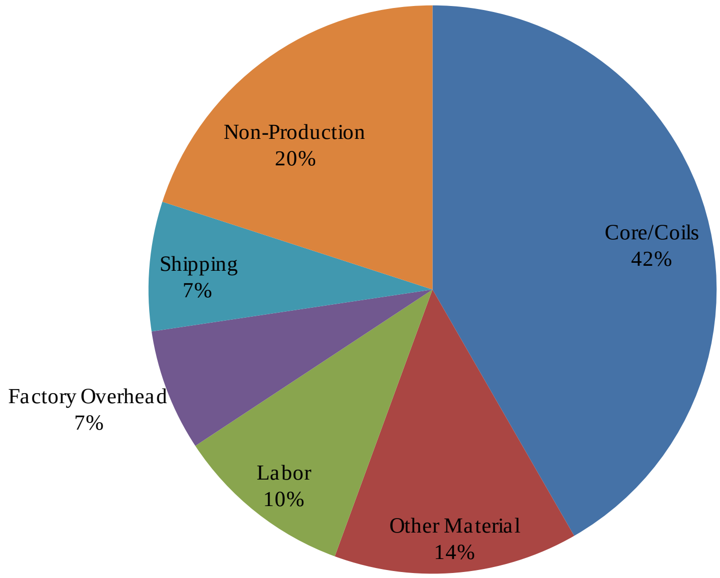

Figure 5.7.1 Manufacturer Selling Price Breakdown, Transformer from Design Line 1

5.7.2 Design Details Report for Transformer from Design Line 7

The following design report provides information on one of the several designs prepared to study the representative unit from design line 7. This is a 75kVA, three-phase, low-voltage, dry-type unit. The design shown here (out of the 43,512 designs in the database) is for M6 butt-lap core steel with aluminum primary and secondary windings, and a $0.50A and $0.10B.

OPTIMIZED PROGRAM SERVICE

CLEVELAND OHIO 101800

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DESIGN ID DL7M6A1A1-BL

STRIP 3-PHASE TYPE TRANSFORMER

FREQUENCY 60.0 KVA RATING 74.94 @ 100.00% DUTY CYCLE

CORE 3.750" STRP STACK 3.938 GRADE M 6 THICKNESS .0140

WINDOW: 4.000 X 12.000 EFF. AREA 14.249 WEIGHT 292.984

WNDG FORM:INS. DIM. 3.875 X 4.062 THICKNESS 0.070 LENGTH 11.875

COIL SPECIFICATIONS

WNDG	WIRE		LENGTH	MEAN TURNS	MARGIN	WT
S1	2X 2(0.102X 0.420)	AL	59.86	23.17	0.250	11.787
P1	2X 2(0.063X 0.188)	AL	354.97	32.72	0.250	19.361

NUMBER OF COILS 3

TOTAL BARE CONDUCTOR WEIGHT 93.444
TOTAL INSULATION WEIGHT 1.493

WNDG	TURNS	LO TAP	HI TAP	LAYRS	T/L	LAYR INS	SEC. INS	BUILD
S1	31.0			3	11.0	1(0.0050)	1(0.0150)	0.682
P1	124.0	111.6	130.2	5	26.0	1(0.0050)	1(0.0000)	0.750

TOTAL BUILD(%) 78.98

WNDG	TAPS: TURNS(VOLTS)		
P1	114.7(444.00)	117.8(456.00)	120.9(468.00)
	127.1(492.00)		

WNDG	INTERNAL DUCTS(80.00)	%EFF	EXTERNAL DUCTS(80.00)	%EFF
S1	2 0.562 X 0.562	END	0.562 X 0.562	END
P1	2 0.562 X 0.562	END		

WNDG	INTERNAL DUCT LOCATIONS
S1	1- 2; 2- 3;
P1	1- 2; 3- 4;

WNDG	INT. DUCT AREA	EXT. DUCT AREA	TOTAL DUCT AREA (FANNED OUT)
S1	255.665	43.851	299.515
P1	388.707	398.948	787.656

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS	TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	480.00 D	432.00	504.00	4.0	53.836	0.10189	1156.83	
S1	116.27 W	120.00 NLV		4.0	208.180	0.00476	1239.12	3.2

	F.L.	N.L.		
			DESTRUCTION FACTOR	1.500
FLUX DENS.	15.514	15.794	LEAKAGE INDUCTANCE MHYS	0.983
CORE LOSS	289.190	299.774	POWER FACTOR	1.000
COIL LOSS	2348.632	0.167	IMPEDANCE %	5.14
EXCIT. VA	749.749	872.645	EFFICIENCY %	96.60
EXCIT. CURR.	0.521	0.606	OPEN ALT. DUCT 3	0.00

AMBIENT TEMP.	20.00	NOMINAL LENGTH	23.250
TEMP.RISE	137.20	NOMINAL DEPTH	13.688
OPERATING TEMP.	157.20	NOMINAL HEIGHT	19.500

WINDING:	S1	P1
TEMP RISE:	137.	135.

COND. I^{2}R LOSS =	2275.3137
COND. EDDY CURRENT LOSS =	5.0585
OTHER STRAY LOSS =	68.2594
K VALUE =	1.0000
% LOSS =	3.0000

WIRE WRAP PER COIL

WNDG	THICKNESS	WEIGHT
P1	0.00500	1.52375
S1	0.00500	0.51395

TEMP.	AT LOW TAP
S1	146.28
P1	144.35

AT REFERENCE TEMP. 170.0^{o}

COIL LOSS =	2436.508
IMPEDANCE % =	5.216

% LOAD	% REG	% EFF	% IR	% IX	% IZ	CORE	LOAD LOSS	TEMP RISE
5	0.11	92.50	0.119	0.222	0.252	299.25	4.67	34.9
10	0.22	95.95	0.225	0.422	0.478	298.73	17.58	35.4
15	0.33	97.08	0.334	0.624	0.707	298.67	39.00	36.4
20	0.44	97.61	0.445	0.826	0.938	298.29	69.12	37.7
25	0.56	97.88	0.557	1.029	1.170	297.90	108.23	39.4
30	0.68	98.02	0.672	1.233	1.404	297.50	156.66	41.5
35	0.80	98.09	0.790	1.437	1.640	297.08	214.87	44.0
50	1.19	98.04	1.170	2.053	2.363	295.70	454.16	54.5
60	1.48	97.89	1.450	2.467	2.861	294.79	675.76	64.1
65	1.64	97.79	1.602	2.675	3.118	294.25	808.60	69.9
75	2.00	97.54	1.934	3.094	3.648	293.07	1126.35	83.8
80	2.19	97.39	2.117	3.305	3.925	292.42	1315.47	92.0
100	3.16	96.60	3.022	4.164	5.145	289.19	2348.63	137.2
125	5.13	94.91	4.871	5.293	7.194	283.12	4741.70	240.4

Table 5.7.2 provides the bill of materials which was calculated from the OPS design details report. This bill of materials uses the raw material prices given in this chapter for fixed and variable materials used in building the transformer. These materials are then marked-up at the bottom of the table to arrive at the manufacturer's selling price. This table provides the bill of materials for a transformer from design line 7, a 75kVA three-phase, low-voltage, dry-type

M6 design, with an aluminum primary and an aluminum secondary. This design uses a butt-lap core configuration, and was generated using a $0.50A and $0.10B.

Table 5.7.2 Bill of Materials for Transformer from Design Line 7

Bill of Materials and Labor for low-voltage, dry-type, three-phase, 75kVA				
A$ Input	$0.50			
B$ Input	$0.10			
Efficiency at 35% load	98.10%			
Material Item	**Type**	**Quantity**	**$ Each**	**$ Total**
Core Steel* (lb)	M6-.014	292.98	$1.46	$427.75
Primary winding* (lb)	Aluminum wire, rectangular, 0.1x0.2, Nomex	58.08	$2.19	$127.20
Secondary windings* (lb)	Aluminum wire, rectangular, 0.1x0.2, Nomex	35.36	$2.19	$77.44
Winding form & insulation* (lb)	Nomex insulation	1.49	$24.50	$36.51
Enclosure	14-gauge steel	1	$131.82	$131.82
Core clamp	-	1	$19.00	$19.00
Duct spacers (ft., drop 2/3)	-	23.56	$0.32	$7.54
Nameplate	-	1	$0.65	$0.65
LV Buss Bar (ft.)	-	7	$1.50	$10.50
HV Terminal Board	-	3	$9.00	$27.00
Impregnation (gal.)	-	1.18	$22.55	$26.61
Misc. hardware	-	1	$7.00	$7.00
Scrap Factor			1.0%	$6.69
Total Material Cost				$906
Total Material Weight (lb)		502		
Labor item		**Hours**	**Rate**	**$ Total**
Lead dressing		0.25	51.52	$12.88
Inspection		0.05	51.52	$2.58
Preliminary test		0.05	51.52	$2.58
Final test		0.10	51.52	$5.15
Packing		0.20	51.52	$10.30
Marking and miscellaneous		0.20	51.52	$10.30
Enclosure manufacturing		1.50	51.52	$77.28
Winding the primary		0.59	51.52	$30.40
Winding the secondary		1.02	51.52	$52.55
Core stacking		1.35	51.52	$69.55
Core assembly		1.00	51.52	$51.52
Handling and slitting factor (on material)			1.50%	$10.03
Total Labor		6.31	51.52	$335
Manufacturing Cost (Material + Labor)				$1,241
Factory Overhead (Materials only)		12.5%		$113
Shipping Cost (Based on Total Weight)		$0.22/lb		$110
Non-production Cost Markup		25.0%		$366
Manufacturer Selling Price**				$1,831

* Indicates those items to which the scrap factor (1.0%) and the handling and slitting factor (1.5% are applied.
** Price based on rounded estimations. The non-rounded price may vary slightly.

Figure 5.7.2 provides a summary of the costs contributing to the total selling price of the transformer from design line 7. For this design, approximately 50 percent of the final manufacturer selling price is direct material and scrap. Labor accounts for 18 percent of the price, factory overhead accounts for 6 percent, and together, shipping and non-production costs account for 26 percent.

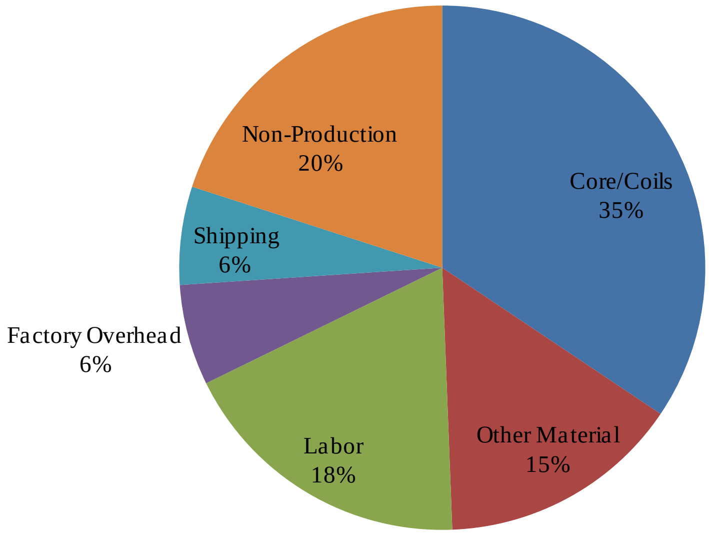

Figure 5.7.2 Manufacturer Selling Price Breakdown, Transformer from Design Line 7

5.7.3 Design Details Report for Transformer from Design Line 12

The following design report provides information on one of several designs prepared to study the representative unit from design line 12. This is a 1500kVA, three-phase, medium-voltage, dry-type unit at 95kV BIL. The design shown here (out of the 43,512 designs in the database) is for M4 core steel with copper primary and aluminum secondary windings, and a \$1.50A and \$0.30B.

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                    OPTIMIZED PROGRAM SERVICE

                CLEVELAND OHIO              101800

                    2010-10-22    11:23:33

DESIGN ID  DL12M4CUAL-(1.5,.3)

STRIP CRUC    3-PHASE TYPE TRANSFORMER

FREQUENCY     60.0            MVA RATING      1.50 @ 100.00% DUTY CYCLE

CORE    10.000" CRUC  STACK     9.950         GRADE M 4     THICKNESS .0110

WINDOW:     15.500 X    52.000      EFF. AREA      76.013    WEIGHT   5832.310

WNDG FORM:INS. DIM.    10.600 X    10.600 THICKNESS    0.156 LENGTH    50.000
```

COIL SPECIFICATIONS

WNDG	WIRE		LENGTH	MEAN TURNS	MARGIN	WT
S1	0.046× 40.000	AL	47.48	43.83	5.000	102.372
P1	0.064× 0.450	CU	3475.55	67.90	5.750	373.996

NUMBER OF COILS 3

TOTAL BARE CONDUCTOR WEIGHT	1429.102
TOTAL INSULATION WEIGHT	80.255

WNDG	TURNS	LO TAP	HI TAP	LAYRS	T/L	LAYR INS	SEC. INS	BUILD
S1	13.0			13	1.0	1(0.0100)	1(0.2000)	2.968
P1	585.0	555.8	614.2	15	1.0	1(0.0000)	1(0.0000)	1.110

TOTAL BUILD(%) 80.44

WNDG	TAPS: TURNS(VOLTS)	
P1	570.4(12158.25)	599.6(12781.75)

DISK INFORMATION

WNDG	DISK	WIDTH	VOLTS/DISK	BREAK	TAPS	SPACE
P1	42	0.536	311.750	0.750	2(0.50)	38(0.375)

WNDG	INTERNAL DUCTS(90.00)	%EFF	EXTERNAL DUCTS(90.00)	%EFF
S1	3 0.750 × 0.750	FULL		
P1			2 0.750 × 0.750	FULL

WNDG	INT. DUCT AREA	EXT. DUCT AREA	TOTAL DUCT AREA (FANNED OUT)
S1	7363.410	1754.248	9117.658
P1	0.000	2710.607	5468.012

DUCT UNDER BARRIER	0.7500
DUCT OVER BARRIER	0.7500

ELECTRICAL ANALYSIS

WNDG	FULL-LOAD VOLTS		TAP VOLTS LOW	TAP VOLTS HIGH	TEST KV	LOAD CURRENT	RESIST. @20 C.	CURRNT DENS.	%REG
P1	12470.00	D	11846.50	13093.50	18.0	40.511	1.01395	1450.90	
S1	274.46	W	277.11	NLV	4.0	1804.300	0.00034	980.84	0.9

	F.L.	N.L.		
			DESTRUCTION FACTOR	1.147
FLUX DENS.	16.208	16.307	LEAKAGE INDUCTANCE MHYS	45.967
CORE LOSS	3799.266	3875.968	POWER FACTOR	1.000
COIL LOSS	11967.563	0.222	IMPEDANCE %	5.68
EXCIT. VA	8331.675	8648.421	EFFICIENCY %	98.96
EXCIT. CURR.	0.223	0.231	OPEN ALT. DUCT 3	0.00

AMBIENT TEMP.	20.00	NOMINAL LENGTH	76.500
TEMP.RISE	107.25	NOMINAL DEPTH	22.834
OPERATING TEMP.	127.25	NOMINAL HEIGHT	72.000

CRUCIFORM PLATE WIDTHS

W1	W2	W3	W4	W5	
10.00	8.95	7.50	5.65	3.35	

STACK HEIGHTS

H1	H2	H3	H4	H5	
3.35	1.15	0.90	0.70	0.55	

RESULTANT GROSS AREA: 79.180 CIRCLE AREA FILL: % 90.0

MIN. WINDING FORM INSIDE DIAMETER: 10.584

WINDING:	S1	P1
TEMP RISE:	107.	76.

COND. I^2R LOSS	=	11599.2158
COND. EDDY CURRENT LOSS	=	78.3668
OTHER STRAY LOSS	=	289.9804
K VALUE	=	1.0000
% LOSS	=	2.5000

WIRE WRAP PER COIL

WNDG	THICKNESS	WEIGHT
P1	0.00500	7.34954

AT REFERENCE TEMP. 170.0 ^{o}

COIL LOSS = 13394.104
IMPEDANCE % = 5.701

% LOAD	% REG	% EFF	% IR	% IX	% IZ	CORE	LOAD LOSS	TEMP RISE
5	0.03	95.06	0.032	0.295	0.297	3872.62	25.33	35.1
10	0.07	97.42	0.063	0.573	0.576	3869.53	98.06	35.7
15	0.10	98.22	0.094	0.852	0.857	3866.36	219.10	36.8
20	0.13	98.60	0.125	1.131	1.138	3863.10	389.55	38.3
25	0.17	98.82	0.157	1.410	1.419	3859.75	610.91	40.2
30	0.21	98.96	0.190	1.689	1.700	3856.32	885.01	42.5
35	0.24	99.04	0.223	1.969	1.982	3852.79	1214.01	45.2
50	0.37	99.15	0.329	2.810	2.829	3841.69	2556.61	55.2
60	0.46	99.16	0.406	3.371	3.396	3833.85	3778.88	63.4
65	0.52	99.15	0.446	3.653	3.680	3829.80	4498.75	68.0
75	0.62	99.12	0.531	4.216	4.249	3821.45	6176.00	77.9
80	0.68	99.09	0.576	4.498	4.535	3817.14	7142.06	83.3
100	0.94	98.96	0.772	5.630	5.683	3799.09	11967.57	107.3
125	1.32	98.72	1.062	7.054	7.134	3774.65	20569.97	142.4

Table 5.7.3 provides the bill of materials which was calculated from the OPS design details report. This bill of materials uses the raw material prices given in this chapter for fixed and variable materials used in building the transformer. These materials are then marked-up at the bottom of the table to arrive at the manufacturer's selling price. This table provides the bill of materials for a transformer from design line 12, a 1500kVA three-phase, medium-voltage, dry-type design with M4 core steel, copper primary and aluminum secondary windings. This design was generated using a $1.50A and $0.30B.

Table 5.7.3 Bill of Materials for Transformer from Design Line 12

Bill of Materials and Labor for medium-voltage, dry-type, three-phase, 1500kVA				
A$ Input	$1.50			
B$ Input	$0.30			
Efficiency at 35% load	99.13%			
Material Item	**Type**	**Quantity**	**$ Each**	**$ Total**
Core Steel* (lb)	M4-.011	5,832.31	$1.59	$9,273
Primary winding* (lb)	Copper wire, rectangular, 0.1x0.2, Nomex	1,121.99	$4.63	$5,195
Secondary windings* (lb)	Aluminum strip, thickness range 0.02 - 0.045	307.12	$1.57	$482
Winding form & insulation* (lb)	Nomex insulation	80.26	$24.50	$1,966
Enclosure	12-gauge steel	1	$795.12	$795
Core clamp	-	1	$125.00	$125
Duct spacers (ft.)	-	1,394.72	$0.56	$781
Nameplate	-	1	$0.65	$0.65
LV Buss Bar (ft.)	-	16	$12.00	$192
HV tap board	-	3	$9.00	$27
HV Terminals	-	1	$135.00	$135
Winding combs (lb.)	-	74.04	$10.00	$740
Impregnation (gal.)	-	27.28	$22.55	$615
Misc. hardware	-	1	$54.00	$54
Scrap Factor			1.0%	$169
Additional scare on core**			4.0%	$371
Total Material Cost				$20,922
Total Material Weight (lb)		8,432		
Labor item		**Hours**	**Rate**	**$ Total**
Lead dressing		1.00	51.52	$52
Inspection		0.25	51.52	$13
Preliminary test		0.50	51.52	$26
Final test		0.75	51.52	$39
Packing		2.00	51.52	$103
Marking and miscellaneous		2.20	51.52	$113
Enclosure manufacturing		8.00	51.52	$412
Winding the primary		23.03	51.52	$1,187
Winding the secondary		2.93	51.52	$151
Core stacking		8.04	51.52	$414
Core assembly		6.00	51.52	$309
Handling and slitting factor (on material)			1.50%	$254
Total Labor		54.70	51.52	$3,072
Manufacturing Cost (Material + Labor)				$23,994
Factory Overhead (Materials only)		12.5%		$2,615
Shipping Cost (Based on Total Weight)		$0.22/lb		$1,855
Non-production Cost Markup		25.0%		$7,116
Manufacturer Selling Price***				$35,581

* Indicates those items to which the scrap factor (1.0%) and the handling and slitting factor (1.5% are applied.
** Additional scrap on core due to mitering process.
*** Price based on rounded estimations. The non-rounded price may vary slightly.

Figure 5.7.3 provides a summary of the costs contributing to the total selling price of the transformer from design line 12. For this design, approximately 59 percent of the final manufacturer selling price is direct material and scrap. Labor accounts for 9 percent of the price, factory overhead accounts for 7 percent, and together, shipping and non-production costs account for 25 percent.

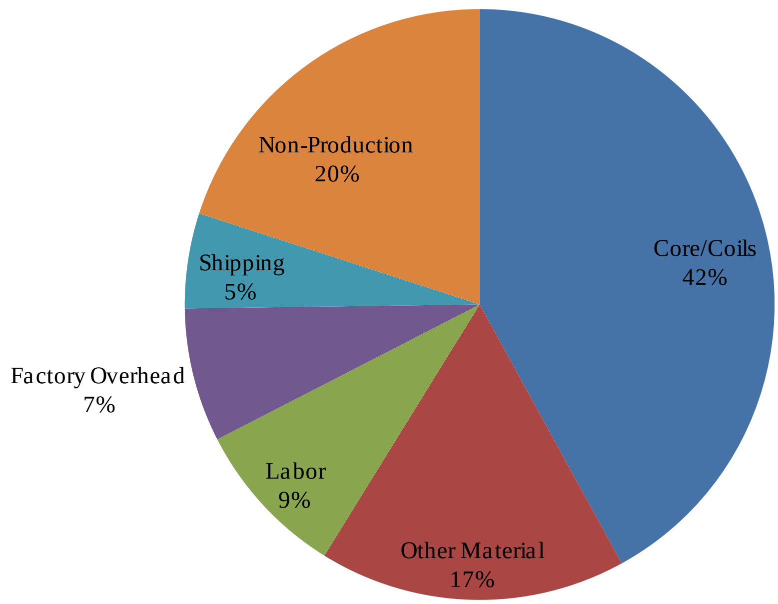

Figure 5.7.3 Manufacturer Selling Price Breakdown, Transformer from Design Line 12